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Executive Summary

Civilian supersonic aircraft carry passengers and cargo at speeds significantly faster than those of conventional subsonic airliners. Though the operation of early commercial supersonic aircraft (European Concorde and Russian TU-144) concluded in 2003, the United States is experiencing a resurgent interest in civilian supersonic flight. This interest is in part due to advances over the last four decades in materials, propulsion, flight control technology, analytical methods, and performance prediction, which have greatly improved the expectation of designing, testing, and operating profitable, efficient, safe, and reliable supersonic civil aircraft (Nicolai and Carichner 2010; McIsaac and Langton 2011). Despite anticipated technical advancements, the physical realities of flight in this regime are such that supersonic aircraft are still likely to have a greater environmental impact (in terms of noise and emissions) than their subsonic counterparts, and will likely exceed the noise and emissions limits set by current subsonic regulations.

Today's supersonic aircraft companies anticipate that the market can support both airliners and business jets. In November 2018, The White House Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute (STPI) to assess the potential future of supersonic civilian aircraft, offering policy options that the Federal Government may consider, as appropriate, to support the commercial supersonic flight industry. We conducted this analysis through a review of the literature, interviews with company representatives and industry experts, and assessments of current commercial efforts using press releases and public data. These recommendations will complement, inform, and possibly accelerate activities undertaken by the Federal Aviation Administration (FAA) under the FAA Reauthorization Act of 2018 (Pub. L. 115–254 Section 181) as well as ongoing efforts within the National Aeronautics and Space Administration (NASA).

Applicable Regulations

Supersonic aircraft will be subject to both U.S. and international regulations. In the United States, the FAA regulates aircraft testing, emissions, noise, and the potential flight paths of supersonic aircraft. The FAA (and thus the United States) bans civilian supersonic flight over land because of environmental and noise concerns. Current regulations (e.g., engine emissions, aircraft noise) are designed for subsonic aircraft (less than Mach 1) rather than supersonic aircraft.

Under the 2018 FAA Reauthorization Act, the FAA Administrator is charged with exercising "leadership in the creation of Federal and international policies, regulations, and standards relating to the certification and safe and efficient operation of civil supersonic aircraft" (Pub. L. 115–254 Section 181), ensuring that applicable regulations meet the preexisting statute to be "economically reasonable, technologically practicable, and appropriate for the applicable aircraft" (49 U.S.C. § 44715). Specifically, the Act directs the FAA to consider addressing supersonic testing, landing and takeoff (LTO) noise, and supersonic flight over land.

The current regulatory environment has significant implications for the technical design of supersonic aircraft, given that regulations regarding noise or emissions directly contribute to factors such as airframe shape and engine design. The lack of clear regulations and the resulting inability to predict a market may be limiting investment, potentially restricting some aircraft design efforts. Regulations that fail to account for integral technical aspects of supersonic flight will likely restrict the physical and commercial viability of these aircraft.

Summary and Analysis of Current Commercial Efforts

At least four U.S. entities are actively designing supersonic aircraft, including efforts from well-established companies (Lockheed Martin's commercial airliner) as well as newer entities focused solely on supersonic flight (Boom's commercial airliner as well as business jets from Aerion and Spike Aerospace); Gulfstream may also pursue a supersonic business jet. The technical details and business goals of these newer companies are summarized in Tables ES-1 and ES-2. Lockheed Martin and Gulfstream did not offer specifics about their programs and are not included in these tables; however, these companies' extensive experience in aircraft development in or near this flight regime lend significant credibility to their potential efforts.

Table ES-1. Technical Details from Companies

Company	Supersonic Speed	Subsonic Speed	Passengers	Takeoff Weight (kg)	Range (nm)	Engine	LTO Noise Stage
Aerion	1.4 M	0.95 M	12	60,300	4,700	GE	5
Spike	1.6 M	N/A	18	52,100	6,200	TBD	5
Boom	2.2 M	<1.0 M	55	77,100	4,500	TBD	4

Aerion's estimated range for its aircraft's cruise at Mach 1.4 is 4,700 nm; its estimated range for cruise at its subsonic speed, Mach 0.95, is 5,300 nm. The aircraft's range for any given route will depend on the ratio of flight time at each speed.

Table ES-2. Business Details from Companies

Company	First Flight	Entry to Service	Estimated Development Cost (Billions)	Projected 10-year Demand	Projected Price of Aircraft (Millions)
Aerion	2023	2025	$4	300	$120
Spike	2021	2023	N/A	500–850	$125
Boom	2025	2027	$6	1,000–2,000	$200

Supersonic airliners (i.e., the efforts from Lockheed Martin and Boom) face several challenges to commercial viability despite internal confidence in demand (from both companies developing the aircraft as well as potential partners and customers). Some critics claim that customers may not value the decrease in flight time as much as is anticipated. In addition, flight time is only one aspect of travel time; supersonic cruise will not decrease the time required to travel to and from the airport, wait at the airport, reach supersonic speeds, and takeoff/land. The benefits of faster cruise are further diminished by the lower relative range of supersonic aircraft, requiring a refueling stop on many routes.

Airline operators (i.e., companies that will purchase the aircraft) will need to consider the impacts of supersonic aircraft on their broader profit margins. For example, offering supersonic flight at the price of subsonic business class seats would likely restrict the cross-subsidy between classes. Because current subsonic flights rely on business class seats to offset economy class losses, moving business class to an entirely different aircraft may adversely affect the bottom line of each subsonic trip, potentially limiting airlines' incentive to offer substantial supersonic service. While new airlines could be built solely to operate supersonic planes, mature airlines will need to consider the impacts across their fleet.

The potential demand for supersonic airliners remains largely uncertain. Supersonic airliners undoubtedly offer a new approach to travel and many individuals may be willing to pay business class fares for a shorter trip in a less spacious cabin.[1] Demand is closely related to the technical specifications of these aircraft, especially range and flight speed.

Many aviation analysts consider the business jet (e.g., the efforts from Aerion, and Spike) a natural point of entry for supersonic aircraft; these analysts anticipate a strong possible demand for supersonic business aircraft, based largely on information from companies pursuing these jets and comparisons to current and past subsonic aircraft. Although companies designing these aircraft cite development costs and demand

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[1] Supersonic aircraft are expected to utilize long, narrow airframes, which may not include the usual amenities of subsonic business class cabins. For example, Japan Airlines has planned to outfit Overture as a single-class cabin.

uncertainty as the greatest risks to their business cases, they also note that lifting the ban on supersonic flight over land would increase the number of viable routes and with it, demand. Some experts are concerned that the Mach 1.4–1.6 speeds targeted by these companies may not offer a sufficient reduction in trip time to justify the increased cost of purchasing, operating, and maintaining a supersonic aircraft. However, market studies conducted by research firms and aircraft companies have indicated that business jet customers are willing to pay significantly more for even small increases in speed.[2] To compare the actual reduction in flight time potential supersonic speeds could offer, Table ES-3 offers the length of time required to travel three routes at three speed points: Mach 0.9 (684 miles per hour), Mach 1.2 (912 miles per hour), and Mach 2.4 (1,824 miles per hour). We calculate this time assuming cruise speed for the full route distance; we do not take into consideration the distance traveled during landing and takeoff operations, during which the aircraft would fly below these speeds, adding to trip time.

Table ES-3. Comparison of Travel Time at Supersonic Speeds

Origin	Destination	Range (nm)	Mach 0.9	Mach 1.4	Mach 2.2
New York (JFK)	Los Angeles (LAX)	2,200	3.7 hours	2.4 hours	1.5 hours
New York (JFK)	London (LHR)	3,000	5.0 hours	3.2 hours	2.1 hours
Los Angeles (LAX)	Beijing (PEK)	5,400	9.1 hours	5.8 hours	3.7 hours

Aerion's approach to its first aircraft (reasonable technical goals, intentions to meet existing requirements), as well as its partnerships with established companies in GE and Boeing, indicate that the aircraft has potential to take advantage of this market. Spike's S-512 project appears to be largely in the design phase; company representatives did not indicate that any hardware is in development or that a major manufacturing facility has been established. While Gulfstream did not share details regarding any specific effort in this area, the company's experience and expertise in developing fast subsonic business jets lend credibility to any potential supersonic efforts.

Contributions of Supersonic Aircraft to Fleet Noise

The FAA Reauthorization Act of 2018 instructs the FAA to establish LTO noise regulations for supersonic aircraft by March 31, 2020. However, companies are already designing their aircraft in absence of these guidelines. Boom is not expecting its 55-

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[2] For example, one analysis showed that in a given year an undisclosed company's staff would have spent 162 fewer hours in flight if they had used a supersonic jet instead of a subsonic alternative, an improvement the company's leadership stated they would have paid significantly to secure (Henne 2005). Additionally, Aerion's website shares an anecdote of a New York company that in 2015 would have saved 142 hours of flight time if it had used the AS2 instead of its subsonic jet.

passenger, three-engine supersonic airliner, Overture, to meet current Stage 5 restrictions;[3] the company instead expects Overture to produce a cumulative noise level between the limits required by existing Stage 4 and 5 regulations for an aircraft of its size.[4] Boom argues that the current regulations would impose major technological design restrictions and claims that the company's current noise goal would not contribute significantly to the noise of the current fleet. However, many others have claimed that Overture's failure to meet existing noise regulations would contribute negatively to overall airport and fleet noise. To determine the impact of this noise level on current airport noise, we compare this projection to the noise levels of the aircraft servicing Dulles International Airport (IAD) and the long-haul aircraft that Overture will likely fly alongside on transpacific and transatlantic routes.

We find that Overture would be louder than the aircraft conducting 80% of the flights servicing Dulles International Airport in 2017. This large difference may be expected, as Overture's takeoff mass is larger than those of the aircraft making a majority of these flights (i.e., many of the aircraft in this sample are smaller—regional jets or private planes).

When compared to the current fleet servicing long-haul routes (i.e., wide-bodied planes primarily comprised of larger Airbus and Boeing aircraft), Overture fares much better: the supersonic aircraft would be louder than the aircraft conducting 16% of transatlantic and 15% of transpacific flights. Even if Overture met Stage 5 standards this comparison would not change significantly: Overture would remain louder than 16% of transatlantic but only 6% of transpacific flights. It should be noted that Overture's expected capacity (55 passengers) is much lower than that of the other aircraft on these routes: in a typical three-class seating arrangement, the eight aircraft considered here hold an average of 383 passengers. Figure ES-1 shows the cumulative noise level of each aircraft that flew transatlantic and transpacific routes in 2016, as well as the noise levels of the Concorde and Boom's Overture.

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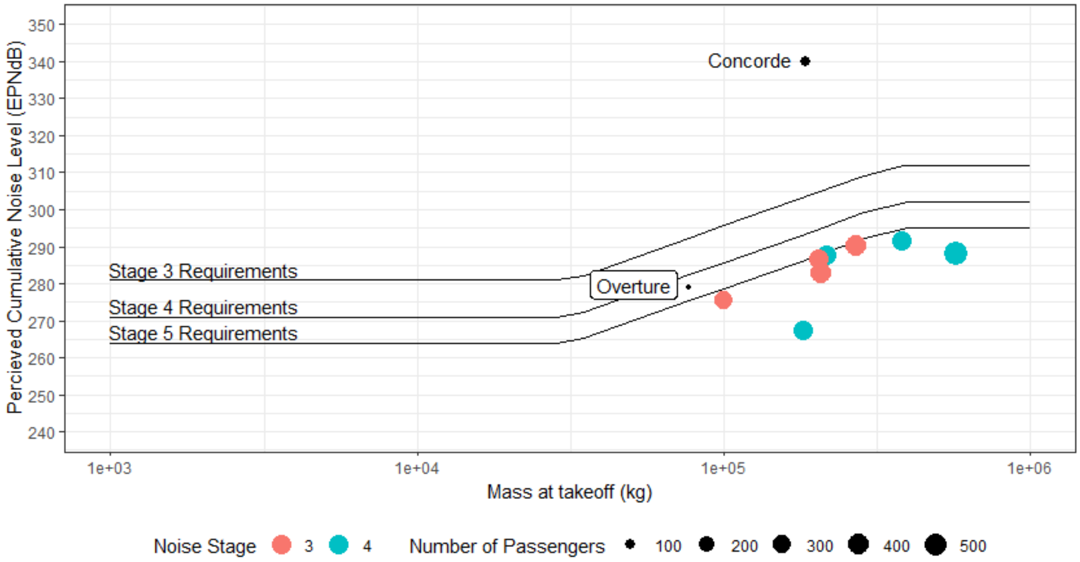
[3] Representatives from Aerion and Spike claim their business jets (the AS2 and S-512, respectively) will be compliant with the existing Stage 5 noise regulations for subsonic aircraft. However, technical experts involved in these projects recognize that meeting these will be a challenge.

[4] Representatives assert that the noise at each point—flyover, takeoff, and approach—will be at least 1 dB below the specific Stage 3 requirement for each point, satisfying this parameter of the Stage 5 regulation. Stage 4 did not require a reduction at any of the three points, only a reduction in cumulative noise of 10 dB.



The requirements plotted here are for a three-engine aircraft of Overture's takeoff weight; the noise levels of the aircraft can be compared to each other but should not be compared to these regulations, as they are larger and subject to different requirements.

Figure ES-1. Overture Noise Comparison to Long-Haul Aircraft

However, many aircraft developed prior to 2017 were already able to meet future requirements for LTO noise, and new models will likely continue to exceed the current regulations, creating a larger gap between the noise levels of Overture and new entrants to the fleet. As research and development expands and supersonic technology improves, it is likely that future iterations of supersonic airliners will also experience a decrease in LTO noise. The projected noise level of Overture is already markedly less than that of Concorde, demonstrating a huge improvement for LTO noise of supersonic aircraft.

Implications of NASA's X-59 Supersonic Demonstration Plane for Commercial Flight

NASA started a low boom flight demonstration (LBFD) mission in 2015, which includes the construction and flight of a Quiet Supersonic Transport (QueSST) aircraft, the X-59. The X-59 will fly at Mach 1.4 with a boom at or below 75 perceived level of decibels (PLdB) and will demonstrate technologies that can be replicated and adapted in future aircraft designs, such as those used for commercial aircraft. In Phase 1, Lockheed Martin is designing and building the single X-59 demonstrator aircraft. In Phase 2, NASA will validate the acoustics of the demonstrator (to include assessing the propagation of the sound wave). In Phase 3, NASA will test and analyze community response to the low boom. The testing will contribute to U.S. Government research and deliberations on a standard for sonic boom noise over land.

Findings from STPI’s Analysis and Options for Government Action

The demonstrated abilities of these companies to achieve each of their technical and business goals vary widely. Despite extensive government progress, the overall regulatory uncertainty regarding designing and certifying supersonic aircraft has led companies to pursue designs and components in absence of specific regulatory guidance, as they move forward on aggressive timelines. Even if these projected timelines are not met, U.S. Government action can have a positive effect in support of supersonic flight in the near- to medium-term, offering a predictable regulatory environment for these commercial efforts.

Several companies are investing millions of dollars in the development of supersonic aircraft, with plans to deploy them within the next decade. The United States Government can take action to support the economic and technical viability of these aircraft by revisiting its regulations for the overland ban based on the potential for Mach cut-off flight and creating an appropriate LTO noise standard. An interim standard for these aircraft could incentivize early development while allowing future iterations to address environmental effects. Considerations of LTO noise should also include a thorough review of air traffic control processes that could minimize environmental effects while maintaining safe operation. Another area that could be crucial to the first generation of supersonic aircraft is enabling Mach cut-off flight; this could support commercial viability of these aircraft and would benefit from action from both NASA and FAA. In order for these endeavors to be successful, these efforts will need to be shared internationally.

The United States is already investing in the longer-term picture of supersonic flight through NASA’s LBFD mission. The realization of boomless cruise and the establishment of a reasonable noise standard will be critical to realizing the potential of supersonic flight. Additionally, developing engines for the next generation of aircraft will be critical for supersonic flight. Catching up on the years of R&D in subsonic engines and overcoming the fundamental challenges of achieving supersonic flight will require innovative and in-depth research; this has already begun on adaptive engines but will likely require additional investment and technology transfer from existing developments. Other research areas such as biofuels can help narrow the supersonic emissions gap while also forwarding subsonic efforts to reduce emissions. Advanced supersonic aircraft efforts rely especially on the LBFD mission, which is acting as both a pathfinder for new technologies as well as the critical path for their implementation. An additional X-59 aircraft helps to mitigate the risk of an aircraft failure that could delay the supersonic industry.

Contents

1. Introduction

A. Background and Goals

Civilian supersonic aircraft hold the potential to transport passengers and cargo at speeds significantly faster than those of conventional subsonic airliners. Airplanes capable of flying faster than the speed of sound have been operating since Chuck Yeager's 1947 flight in the Bell X-1 (Loftin 1985; Hallion 2010; Peebles 2014). Before that flight, there were many who questioned that supersonic flight was even a possibility because of problems related to drag rise and controllability in this flight regime. With the benefit of decades of research and development (R&D), supersonic flight is today almost routine in military aircraft.

Although the history of aviation has included several noteworthy programs, there are no active commercial supersonic airplanes. Early efforts at furnishing commercial supersonic travel (e.g., European Concorde and Russian TU-144, discussed in Appendix A) were unsustainable in their time and failed to inspire even more efficient successors. The United States Government attempted to revive supersonic commercial aviation during the 1990s as part of NASA's cancelled High-Speed Civil Transport program (Spearman 1994; Conway 2005). Again, the past few years have seen a resurgence of interest in the field, primarily in the United States. Companies have begun investing in supersonic aircraft due to a number of reasons, including the low price of oil relative to the 2000s and R&D efforts focused on making supersonic flight more efficient, economical, and environmentally friendly. The environmental advances are most notably exemplified by NASA's successful research on reducing the characteristic "sonic boom" signature of supersonic aircraft with its F-5E Shaped Sonic Boom Demonstrator (Pawlowski et al. 2005; Benson 2013). NASA's research adds to advances over the last four decades in materials, propulsion, flight control technology, analytical methods, and performance prediction, which provide the opportunity to design, test, and operate profitable, efficient, safe, and reliable supersonic civil aircraft (Nicolai and Carichner 2010; McIsaac and Langton 2011). Technologies such as optimized aerodynamics for reduced acoustic signature, quieter engines, synthetic vision, and advanced composite materials are opening the possibility that supersonic aircraft will be commercially viable. In this climate, several U.S.-based companies are pursuing the revival of civilian commercial supersonic flight, both for airliners and business jets.

Despite anticipated technical advancements, the physical realities of flight in this regime are such that supersonic aircraft are still likely to have a greater environmental impact (in terms of noise and emissions) than their subsonic counterparts on a per-aircraft basis. These physical differences combined with the absence of civilian supersonic flight over the last decade and a half has led to regulations inapplicable to supersonic aircraft. As will be described, the U.S. Government can facilitate leadership in civilian supersonics by supporting advances in technology and establishing an appropriate regulatory regime, following the mandate of the recent 2018 FAA Reauthorization Act and existing statute to ensure that the regulations are "economically reasonable, technologically practicable, and appropriate for the applicable aircraft" (49 U.S.C. § 44715).

Several existing domestic and international policies have been identified as hindrances to commercial supersonic flight (Dourado and Hammond 2016; Cato Institute 2018), and specific regulatory changes have been recommended to support commercial supersonic flight (Kratsios 2019). These policies include efforts to streamline the processes for testing supersonic aircraft, clarify allowable noise levels for supersonic aircraft, and remove the prohibition against overland commercial supersonic flight.

B. Objective

In September 2018, the White House Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute (STPI) to assess the potential future of supersonic civilian aircraft, offering options that the Federal Government may consider, as appropriate, to support the commercial supersonic flight industry. These recommendations will complement, inform, and possibly accelerate activities undertaken by the Federal Aviation Administration (FAA) under the FAA Reauthorization Act of 2018 (Pub. L. 115–254 Section 181) as well as ongoing efforts within NASA.

This report includes discussion of the technical challenges of supersonic flight as well as the various regulations affecting the development and potential use of these aircraft, specifically regarding noise at landing and takeoff, the current ban on supersonic flight over land, and the impact of international regulations. It then details current efforts by U.S. companies to develop supersonic aircraft and provides an assessment of the viability of these projects. This assessment considers the feasibility of the technology and development efforts, as well as their potential commercial prospects given the anticipated market and current regulatory regime. The report also offers information on NASA's efforts in supersonics, including its X-59 research aircraft. It then provides options for OSTP action that may support U.S. developments in commercial supersonic flight. Appendices include a summary of previous civilian supersonic programs (Appendix A); relevant text from the FAA Reauthorization Act of 2018 (Appendix B); a list of interviewees and their affiliations (Appendix C); detailed case studies of current company efforts (Appendix D); a comparison of the expected noise of supersonic airliners to that of the overall fleet (Appendix E); a brief description of NASA R&D into supersonics (Appendix F); and discussions of technology and regulatory efforts in the International Civil Aviation Organization (ICAO), Europe, and Russia (Appendix G).

2. Challenges to Supersonic Flight

A. Technical Challenges of Supersonic Flight

Flying beyond the sound barrier presents technical challenges distinct from and exceeding those of subsonic flight. The challenges discussed in this section are inherent to supersonic flight (i.e., flight speeds greater than the speed of sound, Mach 1, but generally less than Mach 5),[5] affecting the range, passenger load, and operability of a supersonic aircraft.

1. Speed and Drag

All aircraft experience drag—the resistive force that an object feels as it moves through a fluid such as air—but this force is greater in the supersonic flight regime; this increase in drag is central to the challenge of supersonic flight. Drag is overcome by propulsive force. The overall drag generated by an aircraft, *D*, can be compared with the generated lifting force, *L*, as an important measure of aerodynamic performance; this is the lift-to-drag ratio, or *L*/*D*. When other factors (e.g., the weight of its structure compared to the amount of fuel on board or the performance of its engines) are held constant, an airplane's *L*/*D* is proportional to its range. As a general rule, *L*/*D* (and thus range) decreases with increasing Mach number (e.g., the Boeing 787 has an *L*/*D* of about 18 at Mach 0.8, whereas the Concorde had an *L*/*D* of only 7.5 at Mach 2). As a result, supersonic aircraft cannot go as far as their subsonic counterparts on the same tank of fuel. The general relationship of *L*/*D* to Mach number is shown in Figure 1.

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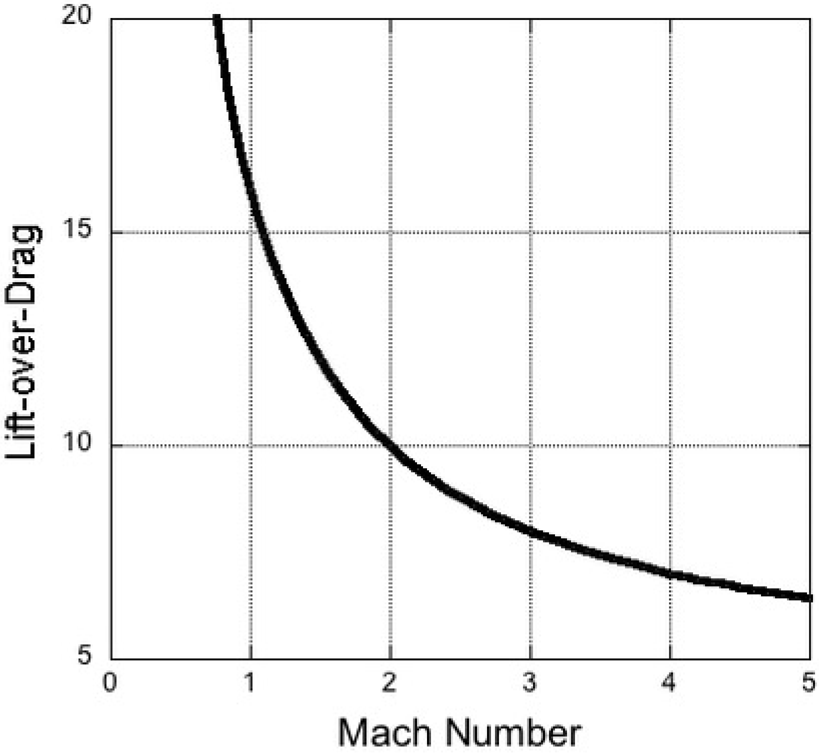
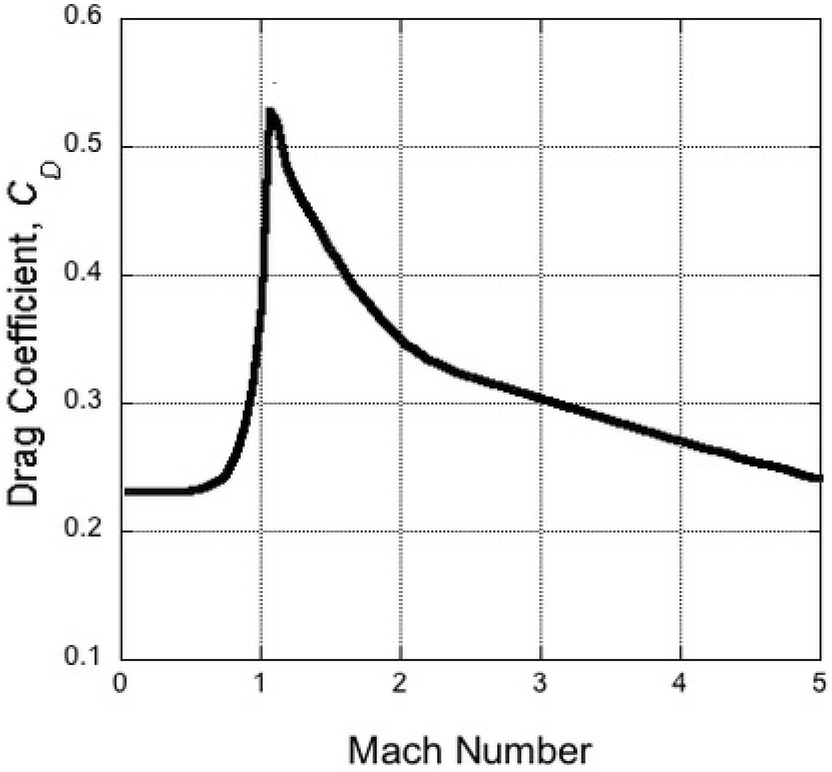
[5] Some companies are planning civilian hypersonic aircraft (i.e., aircraft that will fly in excess of about five times the speed of sound). Boeing's hypersonic jet airliner concept is targeting Mach 5 and could enter service in the next 20–30 years (LeBeau 2018). Atlanta-based Hermeus also envisions a Mach 5 aircraft (Woodyatt 2019). England's Reaction Engines has begun testing subsystems that could support aircraft in this flight regime (Reaction Engines 2018). Among the challenges associated with building a practical hypersonic aircraft, beyond the need for new propulsion systems and advanced materials that can handle the extreme temperatures generated at high Mach number, is the difficulty of flying an optimized hypersonic shape through the transonic regime, as well as during takeoff and landing.



Source: Küchemann 2012.

Figure 1. Representative Maximum Aircraft Lift-Over-Drag, *L*/*D*, as a Function of Mach Number

Aerodynamic performance (which is reflected primarily in range) suffers at increased speed due in large part to increases in drag. Drag is typically characterized by a *drag coefficient*, C_D, which is defined as the drag divided by the density of the air, the surface area, and the square of the vehicle's speed. The drag coefficient grows rapidly with Mach number, reaching a peak value just above the speed of sound, Mach 1. Though maintaining sustained flight near and just beyond Mach 1 is possible, it is typically not desirable, as an aircraft operating in the *transonic regime* near Mach 1 has a higher C_D than an aircraft in either purely subsonic or supersonic flow. This relationship is shown in Figure 2. Given that the drag coefficient is the drag divided by the density of air, the absolute value of drag on an aircraft can be mitigated by flying at higher altitudes, where density is lower. Lower air density can partially offset the increased drag coefficient and increased velocity inherent with supersonic flight. As an airplane continues to increase in Mach number beyond the speed of sound, the drag coefficient generally decreases, but drag itself continues to rise.



Source: Küchemann 2012.

The drag coefficient sharply increases near Mach 1, then gradually decreases as Mach number continues to increase in the supersonic realm.

Figure 2. Representative Drag Coefficient of an Aircraft, as a Function of Mach Number

At and beyond Mach 1, the compressibility of air leads to shockwave formation—sudden changes in pressure, temperature, and density that occur in the flow passing over the aircraft. These shockwaves are the source of the sudden pressure rise that creates the tell-tale sonic boom, a loud noise associated with overflight of a supersonic aircraft. Shockwaves also add additional drag to the aircraft known as *wave drag*; this becomes the dominant source of drag on an aircraft as Mach number increases beyond the speed of sound. Supersonic designs attempt to minimize wave drag by using slender fuselage shapes, though these restrict capacity for passengers and cargo.

At higher Mach numbers, a jet engine's overall propulsive efficiency decreases. Efficiency is defined as the total work that comes from the engine, divided by the total amount of energy that was available in its fuel. In general, the efforts to optimize fuel efficiency have led to maximization of airflow through the bypass fan, resulting in ever-larger subsonic jet bypass (turbofan) engines with large fan blades mounted in huge nacelles that can swallow large amounts of air. However, such engine innovations are not viable for supersonic flight due to the higher drag inherent in a large-diameter turbofan engine as well as the need to decrease inlet velocity. For efficiency in transonic and supersonic regimes, the size of the engine inlet is generally decreased, thus decreasing the overall propulsive efficiency as well. The propulsive efficiency is proportional to range, thus decreasing the overall performance of the aircraft.

Aerodynamic forces on a vehicle's surface are proportional to the local air density and the square of velocity, so a supersonic aircraft flying at the same altitude as a subsonic vehicle will generally experience higher stresses. At high speeds an aircraft's skin will experience high temperatures due to friction with the air (e.g., cruise temperatures on leading edges reach as high as 275 degrees Fahrenheit for a Mach 2.2 design and over 600 degrees Fahrenheit for a Mach 3 aircraft [Heimerl and Hardrath 1965; Jenkins and Quinn 1996]). The higher temperatures are part of the reason that most supersonic craft cruise at higher altitudes (and correspondingly lower density) compared to their subsonic counterparts. High temperatures associated with supersonic flight drive the designs to use high-temperature materials and contribute to greater construction and maintenance requirements than those of subsonic aircraft.

2. Engine Efficiency

While conventional jet engines can operate up to speeds about three times the speed of sound, their overall efficiency drops as speed increases. Manufacturers of subsonic aircraft use larger bypass jet engines that both increase overall efficiency and reduce noise; however, larger bypass engines are not effective for supersonic aircraft as they reduce overall fuel efficiency at these speeds.

Modern subsonic airliners use turbofan engines for increased efficiency (i.e., jet engines with large inlets and fan blades that derive some or most of their thrust from air that flows around the core turbine, in a bypass duct). The bypass ratio is defined as the ratio of the airflow in this bypass duct compared to the amount of air flowing through the core turbine. As a general rule, the higher the bypass ratio, the more efficient the engine. Highly efficient subsonic airliners use engines with bypass ratios as high as 10, and newer engines are higher still (MacIsaac and Langton 2011).

The design of an efficient, effective engine for a supersonic airplane can be a significant challenge; this efficient design is crucial to reducing fuel consumption and adverse environmental impacts. Such an engine must operate across a range of Mach numbers, from takeoff to supersonic cruise. This requires moving parts in both the inlet and nozzle, which bring penalties to weight and maintenance. An efficient supersonic configuration will have diminished performance at lower speeds compared to a more conventional subsonic option. Because of the increase in drag at speeds near Mach 1, supersonic engines must provide high power in acceleration. High-bypass ratio engines will not work at supersonic speeds; less efficient low-bypass ratios, or even simple turbojets without bypass, must be used at increased Mach numbers (Kerrebrock 1992).

However, efficiency is crucial for commercial viability; the best measure of efficiency for a commercial airliner or business jet is fuel burn per payload-distance: fuel is generally an airline's largest expense, comprising 20–35% of operating costs and varying according to market and other forces such as international relations (Hirst 2008; Aerospace 2018).

3. Aircraft Noise

A supersonic aircraft engine will almost certainly be noisier during takeoff than its subsonic counterpart. Optimized for supersonic flow, these aircraft have higher low-speed drag than their subsonic counterparts, thus requiring greater thrust for takeoff, corresponding to higher noise levels. The low-bypass ratio designs required for efficient supersonic cruise correspond to higher jet exhaust velocity, which is the dominant noise source on takeoff. There is potential to mitigate some of landing and takeoff noise, using flow optimization and air mixing to limit jet and fan noise.[6] However, ultimately the higher thrust and jet velocity will lead to more noise than an equivalent subsonic engine.

The sudden pressure jumps associated with shockwaves at supersonic speeds will produce the characteristic noise challenge of supersonic flight: the sonic boom. Work on quiet supersonic airframes has progressed considerably since the late 1990s, including novel aircraft shapes that reduce the sonic-boom signature through careful shaping of the fuselage. In such designs, the shockwave patterns are tailored to reduce their strength on the ground, which may be used to develop an aircraft that can fly over land with an acceptable noise footprint—so called boomless cruise; however, this concept generally only works near a designated Mach number (Benson 2013).

At low supersonic speeds, it may be possible to eliminate sonic boom noise on the ground without extensive shaping of the airframe. The approach, called Mach cut-off flight, is based on the premise that at flight speeds between Mach 1.0 and 1.1 (at certain altitudes), the sonic boom may refract such that it does not reach ground level. At such low Mach numbers, the angles that the sound waves make with the aircraft are very shallow, allowing

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[6] GE representatives note jet noise and fan noise as two opportunities to reduce engine noise. One of the primary causes of jet noise is the highly turbulent shear layer that is formed between the hot, fast-moving engine exhaust gas and the cooler, stationary ambient air. Modern approaches to reducing this noise include 3-D mixer designs using chevrons on the engine nozzle (e.g., the 787 GEnx engine). These technologies effectively mix the engine and air flow, decrease turbulence, and hence reduce noise. On the other hand, fan noise is projected out of the front of the engine, differing during landing and takeoff. During landing, the engines are at relatively low thrust, and the noise arises from interactions between the blades of the turbofan and the distorted airflow entering the engine. In takeoff, where high thrust must be generated, the blades rotate more rapidly such that the tips are supersonic; this generates unique noise modes known colloquially as "buzz saw." Efforts to minimize noise focus on optimizing the flow between the inlet and the fan, and between the fan and the outlet. The intention is to design an engine such that the wake from one component does not create significant noise as it interacts with the next component. It is also common to use noise suppression systems (e.g., liners) in the inlet to minimize fan noise.

the waves to travel large distances before reaching the ground; this results in quieter ground-level noise (Pawlowski et al. 2005; Benson 2013; Sparrow 2018).

Mach cut-off has not yet been demonstrated and represents a significant technical challenge. To move toward implementation, companies will need to prove real-time understanding and control over the boom effects at ground level. This will require significant understanding and modelling of the phenomena, along with precise measurements of the environment around the aircraft and into which it is flying (at supersonic speeds). Even after this effort, research has shown that there will still be a low rumble to reach the ground (Sparrow 2018). The FAA and Aerion have sponsored research into Mach cut-off flight under ASCENT Project 42 at Pennsylvania University, and the project has shown improvements in understanding and modelling of these flights (Sparrow 2018). However, to implement Mach cut-off flight, the companies will require better environmental measuring capability than is currently available (Sparrow 2017). Further, the impact of prevailing conditions such as the jet stream will be large, and it may not be possible to achieve Mach cut-off when traveling west to east if the jet stream is too strong (Sparrow 2018). It will also require substantial testing and demonstration efforts (i.e., the mechanisms will be flight path and speed-specific, so entities will need to show applicability in different situations).

4. Emissions

Environmental concerns were a reason for the cancellation of the American Supersonic Transport in 1971 (even more than questionable fuel efficiency), including concerns regarding engine emissions and ozone depletion (McLean 1985).[7] Many of these issues remain unresolved. For example, in the 1970s concern focused on ozone depletion and subsequent increase in ultraviolet radiation, but by the end of the 20th century a series of studies had shown that supersonic transport would actually create more ozone than it destroyed (Poppoff 1978; Sundararaman 1980; IPCC 1999). These effects depend strongly on the altitude being flown and remain uncertain despite technical and modelling advancements; this includes uncertainties regarding atmospheric chemistry and transport along with projected fleet emissions.

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[7] Congress could have deferred production of the SST while approving manufacture of the first prototypes, which would have enabled NASA, FAA, and other authorities to gain valuable insight into both the design and operation of commercial supersonic transports. As it was, the abrupt cancellation resulted in Boeing shedding fully two-thirds of its workforce—from 150,000 to 50,000, with 8,000 workers losing their jobs in a single day. Seattle was plunged into near economic collapse. Boeing survived on the strength of other programs and also because the government paid back to the company the money it already had invested in the SST program; Boeing Chairman and CEO Thornton "T" Wilson reputedly called the payback "manna from heaven" (Rodgers 1996).

Two aspects of supersonic operation and engine design contribute to emissions concerns specific to these aircraft. First, environmental effects depend largely on the altitude of operation, which is generally higher for supersonic aircraft than their subsonic counterparts; emissions, such as water vapor, deposited at higher altitudes can cause more harm (Jiang et al. 2015). Second, it is likely that supersonic engines will use more fuel and produce more nitrous oxide (per unit of fuel consumed) due largely to the drag and engine challenges discussed above, which will result in a higher environmental impact on a per-aircraft basis (Kharina, MacDonald, and Rutherford 2018).[8]

B. Applicable U.S. Regulations and Policy

Supersonic aircraft are subject to both U.S. and international regulations. In the United States, the Federal Aviation Administration (FAA) regulates aircraft testing, emissions,[9] noise, and the potential flight paths of supersonic aircraft. Because these aircraft are still under development, the FAA is challenged to establish applicable regulations that can accommodate the range of designs under consideration.[10] While FAA regulations apply directly only to aircraft operating in and out of the United States, the FAA works as one of 193 member states of ICAO (ICAO 2019). ICAO is a technical body under the United Nations; though it cannot require individual nations to follow its standards, it provides a global forum for developing international standards that are often adopted by the governments of state parties (FAA 2016).

Under the 2018 FAA Reauthorization Act, the FAA Administrator is charged with exercising "leadership in the creation of Federal and international policies, regulations, and standards relating to the certification and safe and efficient operation of civil supersonic aircraft" (Pub. L. 115–254 Section 181). This includes implementing the previous statute to ensure that the standards and regulations for civilian supersonic flight are economically reasonable, technologically practicable, and appropriate for these aircraft (49 U.S.C. § 44715). Specific considerations may include operational differences between subsonic and supersonic aircraft; costs and benefits of landing and takeoff noise requirements for these aircraft, including impacts on efficiency and emissions; and public and economic

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[8] One analysis estimates that based on high speed, low passenger capacity, refueling requirements, and limited cargo space, supersonic planes will require five to seven times as much carbon per passenger as their subsonic counterparts (Kharina, MacDonald, and Rutherford 2018). At least one company has disputed this analysis, stating that their aircraft will only produce about 1.9 times as much carbon per passenger.

[9] The FAA prescribes regulations that are in compliance with those of the Environmental Protection Agency.

[10] FAA rulemaking uses information from a number of stakeholders, including NASA and private entities. Representatives note that Aerion and Gulfstream have regularly provided such data, but Boom's slipping demonstration date has delayed some aspects of this sharing.

benefits of the operation of these aircraft and associated industry activity. The act addresses regulations applying to supersonic testing, landing and takeoff (LTO) noise, and supersonic flight over land.[11]

In addition to these regulatory efforts, FAA leadership noted that the organization supports R&D on supersonic aircraft through FAA's Aviation Sustainability Center (ASCENT). The FAA has invested nearly $5 million of their total FY18 and FY19 appropriation on supersonic civil aircraft research in ASCENT. These efforts include technology evaluation under Project 10 at Georgia Institute of Technology, supersonic transport forecasting under Project 10 at Purdue University, development of measurement protocols to certify en route noise levels from supersonic aircraft under Projects 41 and 59 at Pennsylvania State University, evaluation of the Mach cut-off Flight operational procedure concept under Project 42 at Pennsylvania State University, clean sheet engine design under Project 47 at Massachusetts Institute of Technology (MIT), and development of tools that can evaluate the impacts of supersonic aircraft engine emissions at University of Illinois under Project 22 and at MIT under Project 58 (co-funded with NASA). The FAA is also in the process of standing up a multi-university ASCENT project that would examine means to reduce jet noise during takeoff under Project 59. The FAA noted other areas of potential R&D for supersonic transport, including developing new procedures for less impactful operations through ASCENT and technology maturation through the FAA's Continuous Lower Energy, Emissions, and Noise (CLEEN) Program Phase III.[12]

1. Overland Ban

The FAA bans civil flight at speeds above Mach 1 over land in the United States due to concerns about sonic boom noise (14 CFR § 91.817).[13] Statute does not require the FAA to ban overland supersonic flight; rather, Congress authorized the FAA to prescribe, as necessary, standards to measure aircraft noise and sonic boom, as well as regulations to control and abate aircraft noise and sonic boom (49 U.S.C. § 44715). Internationally, ICAO policy states the importance of ensuring that "no unacceptable situation for the public is created by sonic boom from supersonic aircraft in commercial service" (ICAO resolution

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[11] Though supersonic flight has faced criticism for its potential to significantly affect the environment due to emissions levels greater than those of subsonic aircraft (Garcia 2019), the 2018 FAA Reauthorization Act does not require FAA action in this area.

[12] More information on the ASCENT and CLEEN programs are available at their respective websites: http://www.ascent.aero & http://www.faa.gov/go/cleen

[13] Operators are able to apply for authorization from the FAA to fly over the U.S. at speeds greater than Mach 1, the requirements of which are outlined in 14 CFR Part 91, Appendix B, "Authorizations to exceed Mach 1."

A39-1, Appendix G). Thus, neither U.S. legislation nor ICAO policy necessitates a comprehensive ban; a standard to limit the noise of the sonic boom would be permissible.

The 2018 FAA Reauthorization Act requires that the FAA review aircraft noise and performance data every other year to determine whether to amend the current ban on supersonic flight over land. The act does not require that the FAA replace the ban on supersonic overland flight with a noise standard, though this biennial review could lead to the establishment of a noise standard for supersonic overland flight.[14] To replace the ban, the FAA will have to determine whether supersonic aircraft can decrease en route noise to an acceptable level; this will require defining an acceptable en route noise level and then determining if technology has progressed sufficiently to meet it.

Establishing a noise level to replace the ban will likely be more challenging than determining that it should exist. NASA leadership notes that efforts to replace this ban with a noise standard require "proof of new design approaches, test procedures and response metrics." Challenges in this area include the lack of relevant data to define the limits (i.e., community data from large, diverse populations) and the need for international acceptance of the standard (Pearce 2019). In determining a potential noise level for supersonic flight over land, the FAA is likely to require ground- and flight-test data regarding the performance and noise of potential supersonic aircraft and would consider the community impact of such noise.

2. Testing

The FAA's authorization of supersonic testing over land requires an exemption from the ban and an investigation of potential environmental impacts. An applicant for license to test supersonic flight will need to provide details per FAA regulations, including: (1) a description and environmental analysis of the test area; (2) information showing that overland testing at speeds greater than Mach 1 is necessary and that tests over water are not sufficient; and (3) an outline of the conditions and limitations applied to ensure that no measurable sonic boom will reach the ground outside of the test area (14 CFR § 91.817, and 14 CFR Part 91, Appendix B). The application also allows the operator to request flights outside of an established test area, though this requires further demonstration that noise will not impact the area. If the tests are conducted at existing test areas, the companies must also receive approval from the government agencies that maintain the testing areas for each use (e.g., U.S. Air Force and NASA).

The National Environmental Policy Act requires that government agencies share a detailed statement for any major Federal action that would significantly affect the quality

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[14] A provision was introduced to the reauthorization act that would have lifted the ban, but it was removed prior to the bill's passing, due at least in part to criticisms of the environmental effects of supersonic flight (Siegal et al. 2018).

of the human environment (42 U.S.C. § 4332(C)). Because of the possible environmental effects of supersonic testing, the Federal agencies involved with either conducting or licensing supersonic testing (e.g., NASA or FAA) will need to conduct an environmental assessment or impact statement addressing this issue. If a categorical exclusion does not apply,[15] the government entity must either provide an environmental assessment that shows the action will not have significant environment effects, or prepare an environmental impact statement (EIS). The EIS process across the entire government has been estimated to take an average of 3.4 years; the process includes several iterations of the EIS itself as well as time for public feedback (deWitt 2008). Interviewees asserted that these processes entail lengthy and costly involvement from the company seeking to conduct a test.

On June 28, 2019, the FAA published a Notice of Proposed Rulemaking to "streamline and clarify the procedures to obtain special flight authorization for conducting supersonic flight-testing in the United States" (FAA 2019a). The proposed rule would update the application for authorization to fly speeds greater than Mach 1 over the United States; it designates the office within the FAA to which potential operators should submit information and questions, clarifies the requirements for the application, and proposes adding a new reason for flight testing to accommodate future noise certification actions (FAA 2019b).[16]

3. Landing and Takeoff Noise

The FAA levies noise requirements on all commercial aircraft; aircraft must meet the prescribed noise requirements at three points individually—lateral (takeoff), flyover, and approach (landing)—and must satisfy a level for the cumulative volume of these three points (14 CFR Part 36). Today, the LTO noise regulations for civil aircraft are those in 14 CFR Part 36 Subpart B, which are implemented for subsonic aircraft[17]; there are currently no U.S. regulations for supersonic aircraft besides the Concorde (14 CFR § 36.301). The FAA has clarified that the Part 36 Subpart B noise regulations do not apply to supersonic aircraft and is working on a proposed rule for noise certification of supersonic aircraft (FAA 2019a).

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[15] A Federal action may be "categorically excluded" from a detailed environmental analysis if the action does not "individually or cumulatively have a significant effect on the human environment" (40 CFR § 1508.4).

[16] Some experts interviewed for the report claim that the FAA changes do not go far enough to enable supersonic testing, asserting that the effort implements only minor changes; it allows flight over water but fails to address the challenges of receiving approval to fly supersonic speeds over land. They recommend that the FAA work to streamline the process for receiving an exemption to conduct supersonic flight tests over land to make these permissions more accessible and less burdensome.

[17] LTO noise regulations are set in effective perceived noise in decibels (EPNdB), intended to account for the community effects of aircraft noise. EPNdB does consider time intervals; it is calculated using a correlation factor for the duration of exposure (14 CFR, Part 36, Appendix B).

For the past several decades, regulators have introduced increasingly stringent requirements for LTO noise levels, recognizing the opportunity for improvement allowed by continued technology advancements in subsonic aircraft and seeking to limit the noise impact of aviation, even as air traffic continues to increase. Stage 4 standards were implemented in 2006, after which applications for aircraft certification must meet Stage 4 noise standards. A Stage 4 airplane must be cumulatively 10 EPNdB lower than what was permitted under Stage 3 requirements. Stage 5 requirements were implemented in December 2017 (14 CFR § 36.103); these require that (1) cumulative noise be 7 decibels lower than permitted under Stage 4 and (2) noise at each of the three measurement points be one decibel lower than permitted under Stage 3. Within the applicable stage, the permitted noise level of each aircraft is determined based on the aircraft's number of engines and maximum certified takeoff mass.[18] Aircraft speed is not currently considered.

The 2018 FAA Reauthorization Act calls for the FAA to revise standards for civilian supersonic aircraft no later than March 31, 2020. We note that the act makes no comment on the change in stringency of standards for supersonic aircraft. The act requires consideration of the technological and economic support for appropriate requirements. The noise standards may consider aircraft weight and engine number, as do the standards for subsonic aircraft; some entities argue the standard should also account for aircraft speed.

Noise requirements introduce a major challenge in balancing environmental protection, technical practicability, and economic viability for supersonic aircraft. There is precedent to consider technical realities in LTO noise regulation. The Concorde aircraft was exempted from specific LTO noise regulations, and instead required to reduce noise "to the lowest levels that are economically reasonable, technologically, practicable, and appropriate for the Concorde type design" (14 CFR § 36.301). Furthermore, subsonic noise regulations account for weight since it "is directly related to the propulsion requirements of an aircraft, and those requirements significantly affect the amount of quieting that can be accomplished, the purpose of the weight parameter in Part 36 is to ensure that all reasonable noise abatement technology is applied for each weight" (FAA 1973). Companies have argued that speed, or at least the power required to exceed Mach 1, is similarly related to propulsion requirements and noise levels; thus an applicable regulation would recognize that these supersonic aircraft, which are of greater capabilities, produce more noise than their subsonic counterparts.[19]

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[18] FAA LTO noise regulations since Stage 2 have used aircraft weight as a parameter. The regulations within each stage apply categorically based on number of engines: two engines or fewer, three engines, and four engines or more.

[19] We should note that this determination relies on a somewhat subjective assessment that aircraft travelling at higher speeds is widely beneficial to the public that would be experiencing higher noise. It is possible that higher weight and thus greater payload capacity contribute more to the public good

Setting a new supersonic noise standard would allow those aircraft to make comparatively more noise than their subsonic counterparts. Higher noise results in a greater area exposed to landing and takeoff noise along with higher volumes, and supersonic noise levels could result in significant increases in perceived noise at some airports (Rutherford, Graver, and Chen 2019). Furthermore, supersonic aircraft will have smaller payload capacity, requiring more air traffic for replacing a subsonic jet based on a smaller payload capacity; supersonic aircraft replacing full subsonic aircraft would require more trips, increasing air traffic.

4. Emissions

The Clean Air Act requires that the Environmental Protection Agency, upon consultation with the FAA, issue aircraft emission standards, currently in 40 CFR Subpart C (42 U.S.C. § 7571). The act also requires the FAA to prescribe regulations to ensure compliance with those standards (42 U.S.C. § 7572). The FAA regulations prohibit fuel venting into the atmosphere (14 CFR § 34.11) and set exhaust limits for gas turbine engines (14 CFR Part 34 Subpart C–D). The regulations include gaseous emissions standards for supersonic engines in 14 CFR § 34.23; this sets nitrous oxide and carbon monoxide emissions limits for aircraft gas turbine engines employed for propulsion of aircraft designed to operate at supersonic flight speeds. The ICAO standards for carbon dioxide emissions were specifically designed for and only apply to subsonic aircraft. While the FAA and ICAO have emission standards for engines capable of supersonic flight, ICAO officials acknowledged in 2009 that these limits are outdated and new designs may require updated standards (Aerospace 2018).

Though the 2018 FAA Reauthorization Act does not require FAA action regarding emissions or climate aspects of supersonic flight, FAA representatives noted that the organization is under some pressure to develop applicable regulations, though many think the effort requires data from aircraft. The United States may wish to be involved in establishing applicable emissions standards—potentially by advocating for an emissions standard, supporting R&D efforts to minimize emissions of supersonic engines and aircraft, or promoting messaging regarding environmentally sound practices. The FAA has already taken steps on these topics, including leading ICAO working groups and funding research with university partners (e.g., ASCENT). Specific areas of technical development and funding mentioned by companies pursuing supersonic aircraft as being potentially useful include efficient or alternative fuel options.

The reemergence of interest in supersonic aircraft comes in the context of broader concern and action regarding aviation carbon emissions. Previous studies have found that

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because they carry more (e.g., more people) on potentially fewer trips—unlike supersonic aircraft, which transport a relatively small number of people faster.

aviation accounts for about two percent of anthropogenic carbon emissions (IPCC 1999). ICAO has resolved to maintain "carbon neutral growth" in the medium-term (2020–2035), preserving the same level of carbon emissions from international flights even as demand for such flights is expected to rise. To meet this goal, ICAO supports advancements in aircraft technology, alternative fuels, airport processes, and has recently developed a global market-based measure (MBM) scheme to help fill the emissions reduction gap. The MBM, titled the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), is a set of standards and recommended practices comprised of four phases:

- 2019–2020: calculating the emissions baseline
- 2021–2023: a voluntary pilot phase
- 2024–2026: a voluntary second phase
- 2027–2035: a mandatory third phase

The United States supports the decision to adopt CORSIA "based on the understanding that CORSIA is the exclusive market-based measure applying to international aviation, and that CORSIA will ensure fair and reciprocal commercial competition by avoiding a patchwork of country- or regionally-based regulatory measures that are inconsistently applied, bureaucratically costly, and economically damaging" (FAA 2019c). The FAA has implemented a voluntary monitor, report, verify (MRV) system that will help to calculate the CORSIA baselines, but it has not yet taken a position on offsetting requirements, which would require rulemaking or other action that "will be addressed at a future time" (FAA 2019c). The baseline will be calculated without the inclusion of widespread supersonic travel, and CORSIA makes no distinction for aircraft speed, number of passengers, or weight.[20]

C. International Cooperation

New supersonic aircraft are expected to mainly operate internationally; according to one prediction, nearly 90% of the supersonic flights will be international (Rutherford 2019b).[21] Thus, the future of supersonic transport relies on not only applicable United States regulations but also those of nations at which the aircraft will be landing and over which they will be flying. International aviation standards and principles are established at the United Nations' ICAO.

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[20] There is some controversy regarding the implications of CORSIA for supersonic transport. Some proponents argue that it would be a chance for supersonic aircraft to offset their increased carbon output (Scholl 2018), while others that it allows loopholes and unnecessary emissions for supersonic transports (Rutherford 2019a).

[21] We note that this assumption of heavy reliance on international flights is due in part to an assumption of the overland ban across most territories (e.g., the United States).

ICAO has not yet developed standards for supersonic aircraft, including LTO noise, sonic boom, and emissions. A note to Chapter 6, ICAO Annex 16 Volume 1 does state that subsonic noise requirements (specifically Stage 3 requirements) may be used as guidelines for supersonic aircraft. As previously mentioned, ICAO resolutions also state the importance of "ensuring that no unacceptable situation for the public is created by sonic boom from supersonic aircraft in commercial service." The resolutions also request that ICAO works to develop "technologically feasible, environmentally beneficial and economically reasonable standards" (ICAO Resolution A39-1).

The ICAO Committee on Aviation and Environmental Protection (CAEP) has been the most relevant to supersonic flight, and a supersonic task group within CAEP Working Group 1 has been monitoring the development of supersonic technologies to inform regulatory efforts on LTO and en route noise (Connor 2004). The ICAO rule-making process has been somewhat inhibited by the lack of existing data for supersonic aircraft, given that these rules typically rely on input data from existing technology, which is not yet available for supersonic aircraft.

Recently, the FAA led the U.S. delegation in negotiations with other member nations regarding the supersonic work programme at the February 2019 meeting of the CAEP. At this 2019 meeting, the CAEP agreed on a 3-year constructive "exploratory study" that will address effects of supersonic aircraft on noise, air, and climate.[22] In contrast, the United States is on track to revise supersonic LTO noise standards no later than March 31, 2020—2 years before the exploratory report will be complete. It is expected that the United States, led by the FAA, will propose these LTO noise standards for international consideration. Additionally, partial data from ongoing NASA projects will be shared at the CAEP meeting in 2022, and full data will be shared at the 2025 meeting. At an ICAO session in 2019, the United States delegation emphasized the importance of a data-driven standard setting approach and prioritizing the exploratory study to "enable technical discussions on future landing and take-off standards in the very near term" (United States 2019).

While the U.S. overland ban remains in effect, supersonic flights originating in the United States are likely to target international destinations such as Europe, Asia, South America, and the Middle East. Each of these entities must allow supersonic aircraft into their airspace; harmonized standards are therefore crucial. While ICAO-CAEP sets the international noise standards, individual nations may choose to establish their own regulations. The U.S. Government must continue to implement a strategy for how to approach international negotiations to facilitate the reintroduction of commercial supersonic flight while addressing international and environmental concerns.

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[22] Some saw the announcement of this study, as opposed to a process to establish new noise standards, as a decision that ICAO will apply existing Stage 5 standards to supersonic aircraft (Rutherford 2019).

3. Current Commercial Efforts

At least four U.S. entities are actively designing supersonic aircraft, including efforts from well-established companies (Lockheed Martin's commercial airliner) as well as newer entities focused solely on supersonic flight (Boom's commercial airliner, and business jets from Aerion and Spike Aerospace); Gulfstream may also pursue a supersonic business jet. This chapter summarizes each company's activities and offers an analysis of the commercial viability of supersonic aircraft. The information regarding each company is based largely on interviews with company representatives as well as their websites and press releases. The analysis of commercial viability is based on interviews with aerospace industry experts, press releases, comparisons with subsonic aircraft, and the open literature; these details are offered in Section C here and interspersed throughout the description of company plans in footnotes. A list of interviewees is included in Appendix C. Further details regarding each effort, including their specific technologies, regulatory challenges, partnerships, and projected business cases, are included in case studies in Appendix D.

A. Commercial Airliners

Lockheed Martin and Boom Technology are pursuing supersonic airliners. Lockheed Martin presented its design for a supersonic airliner in mid-June 2019, though not many details have been made available. Boom is actively developing its aircraft, aiming for a first flight with passengers between 2025 and 2027 (Moynihan and Walków 2019).

1. Lockheed Martin

In June 2019, Lockheed Martin shared its design for a Quiet Supersonic Technology Airliner (QSTA), a twin-engine aircraft that is expected to carry 40 passengers at Mach 1.8 (Neild 2019).[23] The design builds on NASA's quiet supersonic research plane, the X-59 (discussed in Chapter 4), which is under development in Lockheed Martin's Skunk Works Division; the team hopes the X-59 will help prove many of the technologies necessary for the QSTA. One such technology is the shaping of the aircraft, through which the team expects to minimize the sonic boom, reducing it to a "thump" similar to a car door slamming. The plane will require a novel engine; the company's announcement stated it will be medium-bypass and non-afterburning, with 40,000 pounds of thrust. However, a

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[23] Of note, Lockheed has not built a commercial airliner of any kind since the L-1011 Tristar, first flown in 1970. However, the company does have recent experience building supersonic military aircraft, including both the F-22 and F-35 fighter jets.

representative claims that existing engine concepts could potentially be adapted for this aircraft (e.g., through a new low-pressure spool, new fan, and new low-pressure turbine). The long-nose QSTA (and X-59) will require pilot vision through synthetic forward visibility systems as well as conventional cockpit glass, and laminar flow wings will allow increased range and reduced emissions.[24]

Lockheed Martin has not yet publicly shared business plans for the QSTA. The data from the X-59 program will be crucial in addressing regulatory issues regarding supersonic flight, which will allow the aircraft to fly numerous routes. Given the need for regulatory movement, there is no timeline on when this aircraft will be produced.

2. Boom Technology

Denver-based startup Boom Technology is developing a Mach 2.2 airliner, Overture, with commercial service beginning in the mid-2020s.[25] The 55-passenger aircraft is expected to have a range of 4,500 nautical miles (nm) and fly at an altitude of up to 60,000 feet. Based on the paths flown by subsonic aircraft, this 4,500-nm range would allow Overture flights to Europe from much of the United States (e.g., New York to Paris or Dallas to London) but flights from the U.S. (including Los Angeles) would not be able to reach the majority of Asia without a fuel stop.

Boom's current business case does not require supersonic flight over land, and Overture will fly over the United States at speeds lower than Mach 1 as necessary. However, the company estimates that its market would increase by 70% if the ban on supersonic flight over the United States were lifted.[26] Boom is pursuing Mach cut-off flight, which representatives assert is not being prioritized by the FAA or ICAO. Boom considers Overture "meaningfully less costly to operate" than subsonic wide-body aircraft based on internal analyses and estimates that fares on Overture will be comparable to those of subsonic business class seats. The company projects Overture's sale price to be $200 million[27] and estimates the market at 1,000–2,000 planes in Overture's first 10 years of

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[24] Though laminar flow is a promising technology, it poses challenges to minimizing drag; because it relies on an entirely smooth surface, any dent, shift in materials, or foreign object could interfere with drag.

[25] In late 2018, Boom had planned for entry to commercial service in 2023. The flight date for Boom's demonstrator aircraft, discussed in Appendix D, had been projected for late 2017 (Fehrm 2016), though current plans include initial demonstrator flights in 2020.

[26] Boom currently estimates that about 500 routes are economically viable, even with the ban on overland supersonic flight (Wynbrandt 2019). The assumption that this market would increase by 70% if the overland ban is lifted implies that Overture would be able to actually fly over land (i.e., successfully meet any noise standard for overland flight).

[27] For comparison, the Airbus A320neo variant line costs between $99.5–127 million (Airbus 2017) and seats 120–220 passengers in its typical two-class configurations (Airbus 2019b).

production.[28] Boom expects to expand its 100-person workforce to about 500 during the design period, primarily engineers, and scale up for production to 1,000-2,000 manufacturing employees.[29] Initial customers include Virgin Group and Japan Airlines,[30] which have pre-ordered a collective 30 aircraft. Boom estimates that development and certification of Overture will cost $6 billion (Warwick 2019a). The company has so far raised over $162M (PitchBook 2019a).

Engine choice is critical to the viability and performance of the aircraft. As of July 2019, Boom had not selected a provider for its three-engine design and remained in conversation with three companies, which are reportedly self-funding the research. Boom is attempting to manage landing and takeoff without using afterburners, and the company is working to optimize fuel efficiency and minimize maintenance requirements. Boom is hoping to increase engine core life and decrease the fuel consumption; the company expects the fuel burn per seat-mile to be comparable to that of current subsonic business class.[31]

Boom is expecting to reach landing and takeoff noise levels between those required by the current subsonic Stage 4 and Stage 5 requirements applicable to a three-engine airliner of its size. Company representatives claim Overture cannot meet Stage 5 requirements without what they consider major reductions in performance. Appendix E offers a detailed comparison of this noise level relative to other aircraft in service today. In designing an aircraft with landing and takeoff (LTO) noise that will not meet Stage 5 requirements, Boom implicitly assumes that U.S. and international regulators will agree on an alternative standard for supersonic aircraft, or that Overture will receive an exemption.

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[28] Note that this would require an average production rate of 100–200 planes per year. Across all of their product lines, Boeing and Airbus delivered 806 and 800 commercial aircraft in 2018 respectively; these were record highs for both companies (Boeing 2019a; Airbus 2019a). While Boom may have the demand for this number of Overture aircraft, it may not be feasible for a startup to reach these high production levels so quickly.

[29] In 2018, Airbus delivered 800 commercial aircraft with a total workforce of over 80,000 in its commercial aircraft division (Airbus 2018). If Boom wanted to achieve its minimum goal of delivering 1,000 Overture aircraft in the first decade of production, Boom would need to produce 100 planes a year with a maximum of 2,500 employees: 12.5% of Airbus' annual production with 3.1% of its workforce.

[30] Given Overture's projected range of 4,500 nm, long trans-Pacific routes that are of interest to Japanese Airlines may not be feasible without a fuel stop (e.g., Los Angeles to Tokyo is 4,770 nm). Japan Airlines could likely utilize Overture to connect Japan with Honolulu and much of the Asia-Pacific region.

[31] Given the technical challenges to supersonic flight (discussed in Chapter 2A), especially regarding engine efficiency, this expectation may not be realistic.

B. Business Jets

Business jets are under development in three U.S. aerospace firms. Spike's S-512 and Aerion's AS2 are targeting first flights in 2021 and 2023, respectively. Gulfstream has shared some information on potential supersonic business jet efforts as well.

1. Aerion

Aerion expects to fly its 8–12 passenger AS2 business jet in 2023[32] and enter service in 2025, with expectations of selling 500 to 600 aircraft in its first 20 years of production at $120 million each.[33] The AS2 will fly at Mach 1.4 over oceans and Mach 0.95 over land, with ranges of 4,700 nm and 5,300 nm, respectively.[34] A representative estimated that development of the AS2 will cost about $4 billion. Significant investment events include Robert Bass's acquisition of the company in 2002 and Boeing's 2019 investment (noted as several hundred million dollars) for a 40% stake (Trautvetter 2019b; Pitchbook 2019b),[35] though further detail on Aerion's investments have not been made available.[36] FlexJet, a jet leasing company, agreed in 2015 to purchase 20 of Aerion's initial aircraft. Aerion plans to keep the maintenance and support in-house and expects to employ 800–1,000 individuals while building the jet.[37]

GE is working to develop the Affinity series, a family of supersonic engines to support the AS2 and potential future Aerion aircraft (GE 2019); the Affinity engine will use a commercial CFM 56 core. Given the core's commercial heritage and GE's extensive experience in exhaust systems and demonstrations, these components are estimated to be at relatively high technology readiness levels. The AS2 is designed to meet Stage 5 LTO

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[32] This is a slight schedule slip; in 2014, Aerion expected the AS2 to be certified "in or about" 2021 (Aerion 2014).

[33] This production rate is likely plausible for the company; for comparison, Gulfstream delivered 120 jets in 2017 and 121 in 2018 (Trautvetter 2019a). A G650, Gulfstream's recent clean-sheet aircraft, costs about $65 million.

[34] Aerion lists the AS2's range for a full flight at Mach 0.95 as 5,300 nm, and its range for a full flight at Mach 1.4 is 4,500 nm (Aerion 2019).

[35] Boeing has continued study of supersonic aircraft since its effort to develop such a plane ended in 1971 (Warwick 2019b).

[36] As of 2014, Aerion had invested $100 M to develop technologies and optimization design tools in support of supersonic flight (Aerion 2014).

[37] In 2018, Gulfstream delivered 121 aircraft (Trautvetter 2019a) while they employ (including contractors) more than 15,000 people to engineer, manufacture, and service their aircraft. To manufacture 500 aircraft over the first two decades, Aerion would need to produce 25 planes per year with a maximum of 1,000 employees: 20.7% of Gulfstream's annual production with 6.7% of its workforce.

noise requirements.[38] Aerion representatives acknowledge that to reduce noise, it may need to compromise on fuel efficiency. GE representatives expressed some doubt over the feasibility of this goal; GE has not yet completed the analysis regarding feasible LTO noise in the AS2. Through a partnership announced in February 2019, Boeing has taken a minority stake in the company and is providing engineering, manufacturing, and test flight resources, as well as "strategic vertical content," according to the company's announcement (Boeing 2019b).[39]

Aerion is also pursuing Mach cut-off flight for its AS2 aircraft.[40] Mach cut-off has not yet been demonstrated and represents a significant technical challenge. The FAA and Aerion are sponsoring research into Mach cut-off flight and modelling under ASCENT Project 42 at Pennsylvania State University; implementation of this technology, once proven, will depend on FAA action (e.g., to rescind the ban on overland supersonic flight).

2. Spike Aerospace

Spike Aerospace has announced plans for its S-512, an 18-passenger low-boom, Mach 1.6 business jet, which the company plans to fly in 2021. The company expects to sell 500–850 S-512 jets over the first 10 years at $125 million, ultimately servicing a market of more than 13 million passengers each year.[41] The S-512 has an expected supersonic range of 6,200 nm, and the company's business case relies on approval to fly supersonic over land. A representative from Spike expects that operating costs will be comparable to those of other business jets, potentially with a 15% increase.[42] The business and technical details proposed by Spike's representative are quite ambitious, particularly compared to

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[38] Some experts note that this may be a challenge. For example, while GE has not yet completed the analysis regarding feasible LTO noise in a supersonic aircraft, the company estimates that its LTO noise could be 1.3–1.5 times louder than that of comparable subsonic aircraft.

[39] Aerion had previously partnered with Airbus and then Lockheed Martin (Aerion 2015; Lockheed Martin 2017), but these arrangements have ended.

[40] Mach cut-off flight is currently not permitted in the U.S. per FAA regulation 91.817. Allowing it would require a rule change or exemption, in addition to formal FAA certification of the technology. Mach cut-off flight over ICAO member countries (excluding the U.S.) may be permissible per ICAO Assembly Resolution A33-7, Appendix G, depending on the advancement and certification of the technology that enables Mach cut-off flight. Though a significant amount of work is needed to better understand the fundamental science of this technology, the potential payoff in overland flight performance makes this a worthwhile capability for commercial entities to pursue.

[41] The company's estimated market for service may not be feasible. In one conversation, the Spike representative claimed that the S-512 would eventually service a market of 13 million passengers. Assuming a 100% load factor, this would require 720,000 flights of the 18-passenger S-512, or 2,000 flights each day. Given that business jets do not generally fly multiple legs point to point, this level of service is incompatible with the company's estimated fleet of 500–800 jets in the first 10 years.

[42] However, it should be noted that supersonic aircraft are likely inherently less economic due to higher drag.

those of other companies in the area, which are in general pursuing more incremental technologies with more experienced teams.

A representative cited sonic boom as a difficulty moving forward, though Spike has not shared information regarding any hardware,[43] and all noise estimates are based on computational analyses. The company is planning to tailor the aircraft's wing shape to reduce the boom to about 75 perceived level in decibels (PLdB); its website mentions its "patent-pending Quiet Supersonic flight technology," though it offers no details regarding this effort. While the company has not announced selection of an engine, its website states the S-512 will use two engines, each with thrust of 20,000 pound-force (Spike Aerospace 2018). Additionally, a representative stated that some engineering considerations are awaiting information from the NASA X-59 demonstration project.

The representative expects that the S-512 will comply with Stage 5 LTO noise regulations and that trans-Pacific flights will not require a fuel stop.[44] The Spike representative estimates that U.S. regulations will require an additional 10–15 years to develop the ability for supersonic flight; because of this delay, the company is initially focusing on customers in Europe and the Middle East. Spike states the S-512 will fly by early 2021 and begin customer delivery in 2023. This timeline is especially optimistic and will be challenging to achieve, especially without significant progress in the near term. At the January 2019 Global Investment in Aviation Summit in Dubai, Spike Chief Executive Officer Vik Kachoria announced that the company already has two orders for its S-512, though he did not offer additional detail.

3. Gulfstream

Gulfstream representatives expressed confidence in the market for such an offering, citing both market studies and data from current customers,[45] though there was no indication that an effort is currently underway. Representatives claimed a supersonic jet would be successful even with the overland ban, but noted that lifting the ban would

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[43] The company flew a "subsonic subscale" demonstrator in October 2017 to validate "design and aerodynamics," though details were not made available.

[44] Common trans-Pacific routes that could likely support supersonic flight include New York to Shanghai (6,400 nm), Los Angeles to Shanghai (5,600 nm), and Los Angeles to Beijing (5,400 nm). While Spike's targeted range of 6,200 nm would allow the S-512 to complete two of these routes without a fuel stop, this range may be longer than what is plausible. For comparison, the G650, which has a maximum operating speed of Mach 0.925, has a range of about 7,000 nm at Mach 0.8 and 6,000 nm at Mach 0.9; however, supersonic engines generally have different technical requirements (discussed in Chapter 2, Section A), which often impose range restrictions.

[45] This estimate of demand, as well as the company's technical capability to produce fast jets (see above note), is supported by Gulfstream's other business jet offerings, including the G650. According to Gulfstream's website, the company has delivered over 355 G650 aircraft since production started in 2009 (Gulfstream 2019).

significantly improve the business case. A Gulfstream supersonic jet would likely be similar to those of current Gulfstream offerings (e.g., twin-engine aircraft) and would build on Gulfstream's extensive experience.

C. Commercial Viability of Supersonic Aircraft

Technical specifications of the various proposed aircraft have been obtained through interviews, company websites, and press releases. Table 1 presents the technical information provided by each company. Note that the companies' estimates for these metrics vary widely. Lockheed Martin and Gulfstream did not offer specifics about their programs and are not included in Table 1 and subsequent tables; however, these companies' extensive experience in aircraft development in or near this flight regime lend significant credibility to their potential efforts.

Table 1. Technical Details from Companies

Company	Supersonic Speed	Subsonic Speed	Passengers	Takeoff Weight (kg)	Range (nm)	Engine	LTO Noise Stage
Aerion	1.4 M	0.95 M	12	60,300	4,700*	GE	5
Spike	1.6 M	N/A	18	52,100	6,200	TBD	5
Boom	2.2 M	<1.0 M	55	77,100	4,500	TBD	4

* Aerion's estimated range for its aircraft's cruise at Mach 1.4 is 4,700 nm; its estimated range for cruise at its subsonic speed, Mach 0.95, is 5,300 nm. The aircraft's range for any given route will depend on the ratio of flight time at each speed.

The companies' targets for LTO noise levels vary widely. While Boom's team has publicized its goal of meeting noise levels between those required by Stages 4 and 5 for an aircraft of Overture's size, both the Aerion and Spike teams claim their aircraft will meet the applicable noise levels required by Stage 5.[46] However, some experts interviewed are not confident that either business jet will meet Stage 5 requirements. The potential impact of Boom's estimated noise in the context of the existing fleet is discussed in Appendix E.

The estimated ranges of these aircraft, and therefore the companies' claims regarding whether transpacific routes can be flown without a fuel stop also vary. In Table 2, we compare the estimated ranges of each aircraft with the distances of common transatlantic and transpacific routes from two major U.S. hubs. Note that the distance used for each

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[46] Given that Boom is aiming for a higher speed, it is not unreasonable that Overture would produce greater cumulative noise.

route is the minimum possible displacement; it is likely that the actual distance traveled to connect any of these distances will actually be greater.[47] Again, Lockheed Martin and Gulfstream are not included in this comparison.

Table 2. Routes Covered by Supersonic Aircraft

Departure	Arrival	Distance (nm)	Aerion	Spike*	Boom
New York (JFK)	London (LHR)	3,000	✓	✓	✓
New York (JFK)	Paris (CDG)	3,160	✓	✓	✓
New York (JFK)	Dubai (DXB)	5,950	X	✓	X
New York (JFK)	Shanghai (PVG)	6,400	X	X	X
LA (LAX)	London (LHR)	4,700	✓	✓	X
LA (LAX)	Shanghai (PVG)	5,600	X	✓	X
LA (LAX)	Beijing (PEK)	5,400	X	✓	X
LA (LAX)	Tokyo (HND)	4,770	X– ✓	✓	X

The ranges used for each aircraft are 5,300 (at Mach 0.95) and 4,700 nm (at Mach 1.4) for Aerion's AS2; 6,200 nm for Spike's S-512, and 4,500 nm (at Mach 2.2) for Boom's Overture. The AS2's range at subsonic flight of 0.95 is 5,300 nm, and its range at Mach 1.4 is 4,700 nm. We show AS2's ability to connect the considered airports using both its lower supersonic range and its higher subsonic range. For certain flights between nearly coastal airports (JFK-LHR, JFK-CDG, LAX-PVG, LAX-HND), flight over land will be minimal; we assume nearly the entire distance will be covered at Mach 1.4 and use the AS2's supersonic range. For routes that have some flight over land, we offer both the AS2's minimum range (as if the full flight were at 1.4 M) and the AS2's maximum range (as if the full flight were at 0.95 M).

*While Spike's projected range of 6,200 nm allows the S-512 to reach most of these destinations without a fuel stop, it is not clear that this is a reasonable estimate for range of a supersonic jet (see discussion in Chapter 3, Section B2).

A number of factors complicate assessments of viable routes; relevant parameters include demand on the route, reduction in total flight time (which includes ratio of flight over water to flight over land), and the aircraft's ability to cover the range (which is further complicated by issues such as flight path and weather). As a result of this uncertainty and other factors in each aircraft, the companies have varying expectations for the number of viable routes. For example, Boom estimates the Overture will be viable on over 500 routes, even with the ban on supersonic flight over land (Wynbrandt 2019), though some interviewees estimate this number to be closer to 10–15 or even fewer.

To compare the actual reduction in flight time potential supersonic speeds could offer, Table 3 offers the length of time required to travel three routes at three speed points: Mach 0.9 (684 miles per hour), Mach 1.2 (912 miles per hour), and Mach 2.4 (1,824 miles per

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[47] The distance between the two airports is the great-circle distance (i.e., the shortest distance between two points on a sphere). Since these distances are the absolute minimum, it is likely that the actual distance travelled on these routes will be greater for any given flight.

hour). We calculate this time assuming cruise speed for the full route distance; we do not take into consideration the distance traveled during landing and takeoff operations, during which the aircraft would fly below these speeds, adding to trip time.

Table 3. Comparison of Travel Time at Supersonic Speeds

Origin	Destination	Range (nm)	Mach 0.9	Mach 1.4	Mach 2.2
New York (JFK)	Los Angeles (LAX)	2,200	3.7 hours	2.4 hours	1.5 hours
New York (JFK)	London (LHR)	3,000	5.0 hours	3.2 hours	2.1 hours
Los Angeles (LAX)	Beijing (PEK)	5,400	9.1 hours	5.8 hours	3.7 hours

The calculations above assume that the entire trip journey could be taken at supersonic speed—impossible due to not only landing and takeoff operations but also the potential for overland supersonic to be banned over some territories. This ban on speed would decrease the utility of a more expensive supersonic aircraft or a flight on that aircraft, potentially reducing the utility proportional to the percentage of the flight travelled at supersonic speed. For example, even if an Overture aircraft could fly Boom's proposed Boston (BOS) to Dubai (DXB) route without refueling, the aircraft would have to fly over a number of countries, such as those in Europe, which may not readily lift the ban. Table 4 shows the potential impact of these bans on that proposed Overture flight, assuming no refueling stop.

Table 4. Comparison of Flight Time for Different Percentages at Max Cruise Speed between Boston (BOS) and Dubai (DXB)

% of Flight at Supersonic Speed	Time (hr)	Value (hr)
100%	4.0	5.8
90%	4.6	5.2
50%	6.9	2.9
30%	8.0	1.7
0%	9.8	0.0

The Great Circle Distance from BOS to DXB is ~5,800 nm. The time is calculated using Boom's proposed supersonic cruise speed of Mach 2.2, and an assumed subsonic speed of Mach 0.9. The value is the time above a subsonic cruise, which could also be the speed of a subsonic aircraft.

The business claims and cases of each company also vary, as shown in Table 5. The complexity of the technical issues in supersonic flight complicates an assessment of the companies' estimates for development time and cost; this assessment is especially challenging for start-ups, though some have partnerships with established companies. Though subsonic aircraft do not offer a perfect comparison, a reference point for development time and cost may be found among recent clean-sheet designs. For example, the Boeing 787 took 8 years from project start to entry to service and cost about $32 billion (Gates 2011); the Airbus A350 took 11 years and $15 billion (Leggett 2013). The Embraer Legacy 500 took 7 years and $750 million (Taylor 2017), and the Bombardier Global 7500 took 8 years and $1 billion (Marowits 2010).

Table 5. Business Details from Companies

Company	First Flight	Entry to Service	Estimated Development Cost (Billions)	Projected 10-year Demand	Projected Price of Aircraft (Millions)
Aerion	2023	2025	$4	300	$120
Spike	2021	2023	*N/A*	500–850	$125
Boom	2025	2027	$6	1,000–2,000	$200

Technical challenges (detailed in Section 2A of this report) will likely contribute to significant maintenance and operation costs, increasing the costs of supersonic aircraft even beyond initial design and development. In addition to maintenance (e.g., engines) and higher fuel costs (due to inherently lower fuel efficiency), supersonic aircraft will also require specialized training for pilots and maintenance crews. Each of these costs will likely be substantial until the supersonic fleet grows to a sufficient size to enable economies of scale. Despite these challenges, representatives of companies pursuing these aircraft envision that early iterations will establish the market and provide the opportunity to streamline the production and use of subsequent aircraft.

One major aspect of any new supersonic aircraft will be navigating the regulatory and certification processes with the U.S. Government, many aspects of which will be novel relative to the processes for typical subsonic or military aircraft. Companies with extensive experience in these areas (e.g., Lockheed Martin, Gulfstream) may be more quickly able to move forward. However, Aerion has established agreements with legacy companies, both as a provider (General Electric [GE]) and a partner (Boeing); use of these resources and experience can enable Aerion to navigate these issues as well. Newly established companies without regulatory experience (either internal or through partnerships) could benefit from hiring or consulting personnel that can support the aircraft certification process.

1. Commercial Airliner Analysis

Despite internal confidence in demand (from both companies developing the aircraft as well as potential partners and customers), supersonic airliners face several challenges to their commercial viability (Davies 1998). Some critics claim that customers may not value the decrease in flight time as much as is anticipated, though past technology advancements (e.g., in-flight connectivity, video chats) have added to many businesses' communication efforts and not replaced business travel or in-person meetings. In addition, flight time is only one aspect of travel time; supersonic cruise will not decrease the time required to travel to and from the airport, wait at the airport, accelerate to supersonic speeds, and land. Furthermore, the benefits of faster cruise are further diminished on routes that require a refueling stop and include overland segments where supersonic cruise is banned. Some claim the demand for trans-U.S. flights might be limited, as analyses indicate customers may not pay a premium for these options; however, Boom hopes that Overture will counter this challenge by offering fares comparable to what business-class travelers currently pay for subsonic flights. Many in the airline industry expect the supersonic option will generate additional demand for leisure flight, though the potential developers' current market estimates do not depend on increased use.

Airline operators will need to consider the impacts of supersonic aircraft on their broader profit margins. For example, offering supersonic flight at the price of subsonic business class seats would likely restrict the cross-subsidy between classes. Because current subsonic flights rely on business class seats to offset economy class losses, moving business class to an entirely different aircraft may harm the bottom line of each subsonic trip, potentially limiting airlines' incentive to offer substantial supersonic service. First and business class accounts for a small number of passengers on most flights but a large portion of airliner revenue; for example, a 2011 article reports that premium fares were charged for less than 20% of airliner seats but accounted for 40–50% of the revenue for long-haul flights (Mouawad 2011). While new airlines could theoretically be established solely to operate supersonic planes, much of the demand for supersonic aircraft is expected to come from mature airlines, which will need to consider the implications for its entire fleet.

The potential demand for supersonic airliners remains largely uncertain. These airliners undoubtedly offers a new approach to travel and many individuals may be willing to pay business class fares for a shorter trip, even without the amenities of subsonic business class travel.[48] However, the opportunities of supersonic airliner travel are largely dependent on technical milestones; the need for a transpacific fuel stop diminishes the advantage of faster cruise, and the speeds targeted by current efforts may not sufficiently reduce overall trip time.

2. Business Jet Analysis

Many aviation analysts consider the business jet a natural market point of entry for supersonic aircraft. Although companies designing these aircraft cite price and demand as

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[48] Supersonic aircraft are expected to utilize long, narrow airframes, which may not include the usual amenities of subsonic business class cabins. For example, Japan Airlines has planned to outfit Overture as a single-class cabin, making every seat economy.

the greatest issues potentially restricting their business cases, they also note that lifting the ban on supersonic flight over land would increase the number of viable routes. However, this restriction may not be too limiting; for example, a Gulfstream study found that a sample of small civil aircraft (e.g., business and private jets) flew only 25% of their miles over water (Henne 2005).

Some experts are concerned that the Mach 1.4–1.6 speeds targeted by these companies may not offer a sufficient reduction in trip time to justify the cost of purchasing, operating, and maintaining the supersonic aircraft (trip lengths at different supersonic speeds are compared in Table 3, above). However, market studies conducted by research firms and aircraft companies have indicated that business jet customers are willing to pay significantly more for even small increases in speed.[49]

A few experts have noted that in the short-to-medium term, the number of business jets ordered and produced might not present sufficient demand to adequately spur investor and supplier interest. Additionally, many expect it is unlikely that a business jet would generate significant public excitement in supersonics, as opposed to a commercial airliner that would be more relevant to the wider public.

Information shared from companies pursuing business jets, comparisons to current and past subsonic business jets, and insights from aerospace analysts and experts indicate strong possible demand for supersonic business jets. Aerion's approach to its AS2 (reasonable technical goals, intentions to meet existing requirements), as well as its partnerships with established companies in GE and Boeing, indicate that the aircraft has potential to take advantage of this market. Spike's S-512 project appears to be largely in the design phase; company representatives did not indicate that any hardware is in development or that a major processing facility has been established. Although Gulfstream did not share details regarding any specific effort in this area, given the company's experience and expertise in developing very fast subsonic business jets, any formal development effort has strong potential for technical success.

3. Impact of Regulations on Commercial Viability

The current regulatory environment has significant implications for the technical design of supersonic aircraft. Regulations that fail to account for the fundamental differences in supersonic flight are expected to significantly restrict the technical and commercial viability of these aircraft. The lack of clear regulations and the inability to

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[49] For example, one analysis showed that in a given year an undisclosed company's staff would have spent 162 fewer hours in flight if they had used a supersonic jet instead of a subsonic alternative, an improvement the company's leadership stated they would have paid significantly to secure (Henne 2005). Additionally, Aerion's website shares an anecdote of a New York company that in 2015 would have saved 142 hours of flight time if it had used the AS2 instead of its subsonic jet.

predict a market have affected aircraft design choices and likely limited private investment in supersonic aircraft and relevant technology areas. This regulatory uncertainty remains a fundamental challenge.

We note that this regulatory uncertainty is a unique situation when compared to initial subsonic aircraft development: when the first subsonic noise standards went into effect, subsonic aircraft were already in operation. However, government entities are currently working to develop regulations for commercial supersonic aircraft before such aircraft have been produced.

a. Overland Ban

The existing ban on supersonic flight over land restricts the potential market for supersonic aircraft. To support supersonic flight, a route would need sufficient demand (e.g., at the business class or business jet level) and be permissible under current regulations. Experts estimate that this ban has markedly reduced the number of routes that could support supersonic flight, though representatives of companies developing the aircraft claim there are up to 500 viable routes.[50] Potential aircraft developers are preparing to fly supersonic speeds over water and subsonic speeds over land; however, optimizing efficiency in both speed domains presents a significant technical challenge. Many believe this restriction greatly inhibits the commercial viability of supersonic flight, particularly as new shaping technologies and greater understanding are leading to prospective designs that will have greatly reduced (or potentially nonexistent) sonic boom propagation qualities (Pawlowski 2005; Benson 2013; Dourado and Hammond 2016). All companies acknowledge that replacing the ban with an appropriate flyover noise standard would help grow the market and support longevity of production.

The most apparent alternative to such a ban would be to allow unmitigated supersonic flight over land. Repealing the ban would allow significant expansion of the value that supersonic transport can add for airports further inland and thus viable routes. However, allowing all overland supersonic flight would ignore study data showing that sonic booms cause substantial levels of annoyance depending on the frequency of exposure and magnitude of the sonic boom (Fields 1997). The industry also acknowledges the effects of such unmitigated sonic booms and has clarified that routes over land should be prohibited until acceptable levels of exposure have been established (Aerospace Industries Association 2019).

Another alternative to the ban is Mach cut-off flight, which would allow supersonic aircraft to fly at higher speeds over land, potentially expanding commercially viable routes

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[50] Flights that approach the U.S. over water will be permitted. Aircraft will decelerate to subsonic speeds in order to land. However, to service inland cities, the aircraft would need to fly significant distances at subsonic speeds.

and reducing the need to optimize for subsonic speeds. The overland ban currently prevents supersonic aircraft from taking advantage of Mach cut-off flight, ostensibly restricting aircraft from flying supersonic speeds even if there would be limited or no impacts on the ground (Peter 2016). Though a significant amount of work is needed to better understand the fundamental science of this technology, and the noise that will reach the ground during Mach cut-off flight, the potential payoff in overland flight performance is likely worthwhile for government and industry support.

One major goal for supersonic flight overland will be designing the airframe to mitigate the ground level effects of pressure waves.[51] Such a technical advancement could be revolutionary for supersonic aircraft, allowing overland travel without the need to reduce cruise speed. Enabling boomless cruise operations will require setting a route noise standard, likely to be challenging as described in Section 2.B.1. Furthermore, regulatory challenges may continue with setting and adjusting such a noise standard, ensuring that it is technically practicable while minimizing environmental effects. In addition, it will require large investment on the design of the airframe and choosing a design speed that will allow shaping of the pressure waves. Boomless cruise or even Mach cut-off flight could have implications for the utility of supersonic aircraft, as exemplified in Table 6.

Table 6. Comparison of Different Supersonic Cruise Options Over Land

		Trip Time (hr)	
Over Land Cruise Type	**Speed (Mach)**	**BOS-DXB** 40% Over Land	**JFK-LAX** 100% Over Land
Subsonic	0.9	6.83	3.70
Mach Cut-off	1.15	5.98	2.89
Boomless Cruise	1.8	4.88	1.85

Calculated based on an estimated range of 5800nm and 40% trip distance over land between BOS and DXB; and 2200 nm and 100% trip distance over land between JFK and LAX.

b. LTO Noise

The physical differences between subsonic and supersonic aircraft and near term supersonic technology mean that supersonic aircraft cannot meet existing subsonic regulations without sacrificing performance (e.g., maximum speed or fuel performance) or even taking additional risk (e.g., de-rating takeoff thrust or making more extreme takeoff and approach maneuvers). Aerion has reduced the design speed of its AS2 aircraft to Mach 1.4 in an attempt to meet Stage 5 noise standards (along with potential reductions to fuel efficiency). It may be possible for technical advances to overcome the noise challenges

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[51] Spike Aerospace is the only company that claims to be able to do boomless cruise in their first generation of aircraft.

without extreme performance tradeoffs—for example, designing a clean sheet engine for supersonic flight or more R&D into advanced technologies such as variable cycle engines.

Company representatives argue that subsonic noise regulations are overly stringent and should be adjusted to be technologically feasible and economically reasonable for supersonic aircraft. For example, Boom representatives claim that meeting Stage 5 requirements would entail major reductions in aircraft performance, specifically fuel burn; the Boom team is designing Overture to produce LTO noise levels between current subsonic Stage 4 and Stage 5 regulations. Appendix E investigates the implications of this objective on overall fleet noise, finding that, if it entered service today, Overture would be louder than many current planes in service, but quieter than the wide-bodied aircraft that they would potentially fly alongside or ultimately replace on long-haul routes although will have a higher noise level on a per-passenger basis. Ultimately, a determination on LTO noise requirements is likely to be based on economic and technical viability.

Supersonic aircraft can fly subsonic over land, but have to land and takeoff at a relatively permanent noise level. Supersonic manufacturers are much more sensitive to LTO noise regulations (and any related uncertainty) during the design of their aircraft. Thus, even if the United States sets standards specific to supersonic aircraft, it is critical that these are coordinated and shared with the international community. As one company stated: no one will buy a jet that cannot fly to Europe. Without international support for new noise standards (i.e., through ICAO) for supersonic aircraft, companies like Boom will be faced with a difficult decision to limit its number of viable routes or make performance sacrifices to access some markets.

Uncertainty on LTO noise regulations may be limiting new supersonic manufacturers and their potential operating partners. For future manufacturers (e.g., Lockheed Martin) or new iterations of supersonic aircraft, LTO noise requirements will determine the technical difficulty of aircraft design, specifically the requisite engine investment. Additionally, the small margins with noise requirements have also led manufactures to suggest a number of changes to airport operations to mitigate LTO noise.

c. Airport and Airspace Operations

Adjustments to airport processes may further enable supersonic travel. Some companies have identified aircraft processes that may enable quieter LTO as well as more seamless integration into existing airport systems (e.g., access to shorter runways). One such option is to use advanced takeoff and climb procedures, including accelerated climbs and automatic throttle variation (called programmed lapse rate). Both of these procedures could reduce measured takeoff noise but will require departures from normal reference procedures (Berton 2017). Another option on approach is expanding the use of a steep approach (i.e., approach angles above 3.77 degrees, typically around 5.5 degrees) that exceeds standard approach path angles (i.e., between 2.75 and 3.77 degrees). Steeper approach angles may allow supersonic aircraft to decrease approach noise, decreasing thrust and thus engine noise.[52] Currently, steep approach requires specific FAA certification (FAA 2012); an FAA representative noted that the FAA rarely allows steep approach at U.S. airports except for obstacle avoidance. Certification is more common for some international airports with tough obstacles and noise rules at certain airports (e.g., London-City). This certification is generally accessible; several aircraft are certified, including larger aircraft such as the Airbus 318 (Airbus 2009).

These proposals to allow supersonic aircraft to use advanced takeoff and approach procedures also highlight some of the challenges of integrating supersonic flight with the subsonic fleet, especially with novel air traffic patterns. For example, instrument landing systems (ILS) are permanently tuned for low approach angles, forcing aircraft on steep approach to other approach aids.[53] Furthermore, mixing steep approach or accelerated takeoff with the rest of the subsonic fleet could impact the safety and the capacity of the airspace, requiring air traffic controllers to manage multiple flight paths. These challenges, especially safety considerations, must be critically understood before making any changes to enable supersonic flight. However, a comprehensive look at air traffic control (ATC) for supersonic flight could enable an economical approach to reducing environmental effects (National Research Council 2001).

Company representatives observed that some other aspects of the ATC system present barriers to supersonic flight, such as the limited ATC in upper airspace (supersonic planes are expected to fly in Class E airspace, a regime that lacks cooperative de-confliction mechanisms) (Hunter 2015).[54] NASA representatives noted that introducing supersonic transports to the ATC system involves a number of challenges; maneuvers required to fit into air traffic patterns could require substantial course changes, burn additional fuel, and extend trip times (Sawyer, Silsby, and McLaughlin 1968).

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[52] Steeper approach will not necessarily decrease overall noise, as increased airframe interactions can lead to greater non-engine approach noise.

[53] Details regarding the ILS are available in FAA (2016a). Microwave ILS may be amendable to steep, instrumented approach (National Research Council 2001).

[54] Most commercial airline traffic operates in Class A airspace during cruise. Class A airspace exists between 18,000 feet MSL and 60,000 feet MSL, above which it reverts to Class E airspace. Class A airspace introduces operational requirements that give ATC greater ability to reduce separation or otherwise allow efficient management of larger traffic volumes. For this reason, all Class A traffic must be under ATC control with an appropriate flight clearance; Class E airspace is less operationally restrictive.

4. NASA's Low Boom Flight Demonstration Mission

Many technologies that will enable supersonic flight require further research and development (National Research Council 2001); some of these efforts are being addressed by NASA, primarily in its Aeronautics Research Mission Directorate (ARMD). ARMD focuses on two areas of research affecting supersonic aircraft: environmental issues (sonic boom, landing and takeoff noise, emissions at high altitude) and technical efficiency (weight, aerodynamic performance, propulsion). NASA currently spends about $15 million annually on technology efforts that could contribute to the development of commercial supersonic aircraft, focusing on airframe, engine, emissions, and aircraft noise. These supersonic-specific efforts build on related NASA research in areas such as subsonic emissions during landing and takeoff (LTO), and high-temperature materials research; these efforts are detailed in Appendix F.

Many experts, including NASA leadership, consider the ban on supersonic flight over land the greatest barrier to supersonic flight (Pearce 2019). NASA also recognized that data on community response to the noise caused by supersonic flight could be a crucial input to any effort to replace the ban with a noise standard. ARMD started a low boom flight demonstration (LBFD) mission in 2015, which includes the construction and flight of a Quiet Supersonic Transport (QueSST) aircraft, the X-59. The LBFD project builds on a series of programs that originated at NASA and transitioned to the Defense Advanced Research Projects Agency (DARPA), then moved back to NASA. NASA's focus on the LBFD led to a decrease in some relevant areas of environmental (e.g., emissions and LTO noise) and technical (e.g., aerodynamics, propulsion, and structures) research.

NASA's LBFD project includes the development of the X-59 Low Boom Flight Demonstrator by Lockheed Martin Skunk Works at its facility in Palmdale, California. The X-59 will fly at Mach 1.4 with a boom at or below 75 perceived level of decibels (PLdB) and will demonstrate technologies that can be replicated and adapted in future aircraft designs, such as those used for commercial aircraft.[55] The X-59 program is simply targeting low boom; it is not trying to develop an efficient or viable aircraft and does not attempt to address other issues (e.g., drag, speed, LTO noise, fuel efficiency, or high altitude

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[55] The low-boom technology has been validated through wind tunnel testing and is expected to reach technology readiness level 6 after system and subsystem components are integrated into a prototype demonstration prepared for the relevant environment.

emissions). The X-59 project intends to leverage NASA efforts and expertise to demonstrate that shaping of the aircraft can reduce the noise of overland supersonic flight to a level that will be acceptable to the general public.[56] Additionally, it will include the development and demonstration of capabilities to measure the acoustic characteristics of the X-59 and the atmospheric effects of the sonic boom signatures (Pearce 2019).

The LBFD project includes construction of only one X-59 demonstration plane. Individuals working on the project note that the decision to build only one aircraft (instead of multiple planes both for redundancy and to allow for more frequent testing and different conditions) was based on budgetary restrictions. To stay within these restrictions, Lockheed is meeting NASA's requirements with the smallest and slowest plane possible that will still provide acoustical data relevant for a small supersonic transport. The team is targeting speeds of Mach 1.4, the lowest speed that offers data valid up to Mach 1.8; speeds greater than Mach 1.8 bring greater engine and LTO noise challenges. In addition, the X-59 will be piloted.

The full mission has three major phrases. In Phase 1, Lockheed Martin is designing and building the single X-59 demonstrator aircraft. In Phase 2, NASA will validate the acoustics of the demonstrator (to include assessing the propagation of the sound wave). In Phase 3, NASA will test and analyze community response to the low boom.[57] The project life-cycle cost for the development and validation of the X-59 (i.e., Phases 1 and 2) is $583 million. This cost does not include community response test processes and flight operations that will be conducted in Phase 3 (Pearce 2019).

NASA conducted initial community tests in 2018 using an F-18 supersonic dive simulation maneuver in its Quiet Supersonic Flight 2018 (QSF18) research campaign, which yielded feedback that a sonic boom at or below 75 PLdB would not be disruptive. According to NASA representatives, QSF18 was intended to understand requirements and reduce project risk for Phase 3 of the mission; additionally, the community size was considered too small to support the development of a noise standard. The F-18's dive

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[56] To meet this goal, the X-59 creates a pressure distribution that more closely resembles a sine wave, rather than the traditional N-wave. The design of the airframe adjusts the lift distribution to tailor the distribution of shocks and expansion waves associated with supersonic flight. The plane is shaped so that the separated shocks never coalesce as they do in traditional supersonic aircraft; this gives the X-59 a supersonic "heartbeat" sound in the far field, rather than the disruptive single pulse of the N-wave. NASA's acoustic validation efforts will include assessing the propagation of the sound wave. Additionally, NASA is working with Rockwell to develop CISBoomDA, a real-time boom prediction capability that could contribute to flight planning and in-flight changes (NASA 2016).

[57] Phase 1 (Aircraft Development, fiscal year [FY] 18–22) will include detailed design, fabrication, integration, ground tests, checkout flights, and subsonic and supersonic envelope expansion. Phase 2 (Acoustic Validation, FY22–23) will include aircraft operations and facilities as well as research measurements and capabilities). Phase 3 (Community Response, FY 24–26) will include an initial community response overflight study and 4-6 campaigns over representative communities and weather across the U.S. (Pearce 2019).

maneuver causes a large focused boom at the front-most aspect of the boom footprint, not accurately replicating the noise signature of a supersonic flyover.

We note that the focus of NASA's QueSST program differs significantly from commercial priorities. Aerion and Boom are primarily concerned with minimizing LTO noise and ensuring that applicable regulations are appropriate and attainable. These companies claim that from a commercial standpoint, supersonic flight could be reestablished first using oversea routes, even in absence of low boom flight and continuation of the ban on supersonic overland flight. The issue of boom during flight, which is NASA's focus with the LBFD mission, is currently a secondary concern for commercial entities trying to get off the ground. It is clear, however, that these companies would benefit from the ability to fly over land, especially as their current ranges do not allow for many popular overseas routes without a refueling stop (see Chapter 3C). These companies would especially benefit from any implications for Mach cut-off flight since their first generation aircraft will not boast airframes capable of boomless cruise.

The community response information from Phase 3 will contribute to U.S. Government research and deliberations on a standard for sonic boom noise over land. It will also yield validated hardware, test methodology, improved computational fluid dynamics development, and processes for community testing that intend to inform and improve commercial processes. The X-59 project team will collect feedback on the perception of the aircraft's noise on the ground as X-59 flight tests are conducted over regions not accustomed to loud overflight. The outreach necessary—including developing survey questions and methods—is expected to be the greatest challenge in the community response phase. The dose response curves from community testing will allow operators to determine the flight options for a certain plane, atmospheric conditions, and community. The project team intends to provide data from the community tests to ICAO. NASA will initially contribute partial data to the ICAO's CAEP 13 meeting in 2025 and data from the full test program to the CAEP 14 meeting in 2028. ICAO regulatory efforts are discussed in Chapter 2B3; international regulatory and technical efforts are detailed in Appendix G.

The LBFD project currently expects a first flight of the X-59 in the third quarter of FY 2021, with community tests beginning in late in FY 2022 or early FY 2023. NASA envisions a 3-year effort with 4-6 community tests in different U.S. locations (i.e., the final data will be generated in late FY25 or early FY26).[58] The program will need to conduct a National Environmental Policy Act process for each of the communities, which the team noted as a significant challenge. The lead time between development and flight is attributed

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[58] The team noted that ideally, some test flights would take place over other countries, to build support for the effort and understanding of the technology. To address the importance of international buy-in and share the results of the X-59, NASA could invite ICAO personnel to attend these test flights, experiencing first-hand the overland noise of the X-59 aircraft.

to time necessary for technological development by suppliers as well as reviews and testing. The next major milestone for the X-59 is a critical design review (CDR) in September 2019. It should be noted that Boom’s Overture and Aerion’s AS2 are not expected to incorporate technology from NASA’s X-59 (discussed in Chapter 4A) due to the longer timeline of NASA’s demonstrator (Norris 2018).

5. Potential U.S. Government Actions

The United States Government has many opportunities to support the development and implementation of civilian supersonic aircraft; these are enabled by and will continue to support ongoing efforts by the FAA and NASA. Government action can address the major factors challenging both the technological development and commercial viability of these aircraft—supersonic flight over land and LTO noise requirements—as well as other issues, including testing. As detailed in this report, Federal agencies are already making significant efforts to support civilian supersonic flight; this chapter outlines potential further actions on the Federal level.

A. Supersonic Overland Flight

1. Support the Implementation of Mach Cut-Off Flight

Several U.S. companies are pursuing Mach cut-off flight, a procedure in which aircraft fly just above Mach 1 while generating no significant boom at ground level. As an internal FAA memorandum indicated, Mach cut-off may someday prove "to be a viable operational profile, but even then, its use over land in the United States would require an exemption from §91.817 or a change in the rule language itself. Further, any technology associated with its use would likewise need to be certificated for installation on aircraft" (Peter 2016). Research showing Mach cut-off flight as viable for controlling and eliminating the adverse effects of sonic booms would be a clear pathway to allowing supersonic flight under certain conditions, and this option should be examined closely.

a. Provide a Regulatory Pathway for Mach Cut-Off Flight

The 2018 FAA Reauthorization Act charges the FAA with assessing the need for a ban on overland supersonic flight every other year, reviewing available data on aircraft noise and performance (Pub. L. 115–254 § 528(d)(2)). Mach cut-off flight offers a near-term solution to mitigate the noise of overland flight.

Companies are not likely to pursue certification for Mach cut-off flight until around the time of their entry to service (e.g., 2025–2027). For example, Aerion plans to implement the necessary technologies in the 2025–2026 timeframe, around the AS2 is meant to enter service. To be able to implement Mach cut-off flight in the United States, however, the overland supersonic ban will need to be replaced—for example, by a performance-based standard that allows companies to prove they can fly at low supersonic speeds with limited noise effects at ground level. To support company timelines, the FAA would need to begin revisions by the 2024-mandated review. An earlier timeframe would assist with testing and regulatory certainty. Ultimately, following a successful LBFD regime, the FAA can set a new noise rule, generalizing the noise standards for en route noise; however, an earlier rule focused on Mach cut-off flight would allow current manufacturers to exceed the sound barrier over land sooner.

b. Research Licensing Mach Cut-off Flight

Certifying Mach cut-off flight, even in 5–7 years, will be challenging. The FAA has already been funding modelling and other research in Mach cut-off flight through the ASCENT program; the FAA should continue research to understand and model the phenomenon and its environmental implications, as well as develop approaches to how it might be licensed and operationalize a regulatory pathway—including gathering data. Companies should be encouraged to provide Mach cut-off data from demonstrator or full-scale test flights to the FAA in advance of new rules or guidance.

Additionally, FAA and NASA could work together to consider whether any portions of the LBFD mission could be used to inform a Mach cut-off certification process in advance of the ability to set a high fidelity noise standard. An example of an area of research would be adding new test regimes to approximate the profile of Mach cut-off flight. The LBFD mission will eventually lead to an en route noise standard, but could also enable the licensing of Mach cut-off flight in advance of such a standard.

c. NASA and the FAA Should Support Environmental Modelling and Sensing Technologies

Critical to the implementation of Mach cut-off flight is the ability to accurately measure and model the environment around the aircraft in real time to give the pilot feedback on course and speed corrections to limit the impingement of the sonic boom at ground level. Previous research has shown promise with existing technologies, especially NASA's Cockpit Interactive Sonic Boom Display Avionics (CISBoomDA) project (NASA 2016), but it will require further maturation for deployment (Sparrow 2017). NASA should support the efforts private companies need to implement Mach cut-off flight, either by sharing existing technologies or by jointly funding research. There may be overlap and synergies between the LBFD project and advancing Mach cut-off flight.

2. Expand NASA's QueSST Mission to Include a Second X-59 Plane

Currently, NASA's X-59 is the United States' major research effort in supersonic flight; however, the project has planned for only one research aircraft. The LBFD mission is key to the long-term vision of supersonic flight, and having only one research plane may expose this vision to unacceptable risk. As past experimental efforts have shown, redundancy can be key to the successful accumulation of relevant data. Although accidents resulting in aircraft loss have been limited as technologies improve (e.g., more reliable flight propulsion, improved flight control architectures, tailored aerodynamics, improved systems monitoring and fault detection, new and improved materials, and better training and procedures), accidents do still occur, most taking place well outside the anticipated high-risk portions of a research airplane's envelope. A review of nearly two dozen NASA, National Advisory Committee for Aeronautics, U.S. Air Force, and U.S. Navy flight research programs on various experimental aircraft and technology demonstrators, while confirming the undoubted improvements in flight safety mentioned above, reveals the wisdom of procuring at least two research aircraft. Single aircraft programs have been rare, but when accidents or damaging incidents have occurred, programs have suffered delays and even termination. Multi-aircraft programs likewise suffer delay when an aircraft is damaged or lost, but are inherently more resilient.

If the X-59 plane was lost, especially before any community testing is conducted, it could set back regulatory processes for years if not decades. Furthermore, it makes little sense to invest at great cost in the infrastructure and logistical supply chain to support development of a single aircraft with the expectation that it will suffice for achieving mission goals, and, indeed, survive to do so. Project staff noted some difficulty acquiring subsystems, saying that potential contractors are more interested in larger projects than a single demonstration plane. A second or third aircraft adds a vital measure of project assurance and flexibility at relatively little cost.

In addition, multiple planes would allow for more test programs, empowering the project team to consider and test a wider variety of factors. A second aircraft could enable the project team to investigate different methods of addressing the sonic boom noise, and potentially different noise profiles such as Mach cut-off flight. Increasing ARMD's budget for the QueSST project, including construction of at least one additional X-59 plane, could greatly support this effort. The cost of a second aircraft can be estimated at about 80% of the cost of the original (e.g., Moore 2015)[59]; note that the design, build, and flight acceptance of the X-59 is expected to cost $583 million (Pearce 2019). Since manufacturing work has already begun on the first plane, NASA leadership would expect a second plane to be ready in time for community testing (Phase 3), which is when a second aircraft would be most valuable both to mission risk and speeding up the timeline.

3. Accelerate Outputs of NASA's LBFD Mission

The implementation of aircraft that can cruise at about Mach 1.8 with limited noise impacts relies on the timeline of the LBFD mission, both to set the appropriate regulations and to demonstrate the technology. At least two companies are waiting on the results of the

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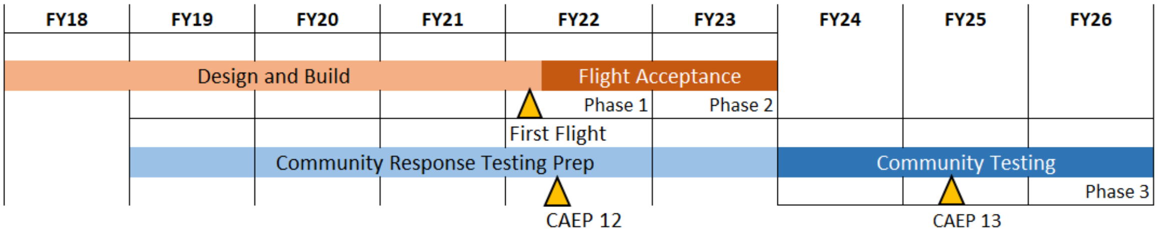
[59] For further discussion of cost estimates, see Benkard 2000; Henneberger 1993; and Wright 1936.

project for their supersonic ventures. It is worth considering whether some of the results of the pathfinder LBFD mission can be accelerated.

The LBFD project has begun manufacturing of the X-59, and NASA project leaders have indicated that virtually nothing can move the entire project left on the timeline, shown in Figure 3. It may be worth considering whether any options would provide earlier results without accelerating the mission. One example is an option already mentioned in this report: building a second X-59 could accelerate community testing. Other options would include tightening the flight acceptance timeline of the X-59 or assessing how to shorten the process to approve testing (e.g., project managers note that completing the National Environmental Policy Act process for each test location presents a significant challenge in terms of resources and time, though government efforts to streamline this process may be useful).



Dates from Pearce 2019.

Figure 3. Timeline of the LBFD Mission

Other than the potential to inform Mach cut-off flight, the LBFD mission informs at least two efforts critical to future supersonic aircraft. The first is determining regulations for supersonic flight over land, both domestically and in international deliberations. Currently, the mission is on track to deliver partial information in time for ICAO's Committee on Aviation Environment Protection (CAEP) 13 meeting in 2025; information from the entire project will be shared with the CAEP 14 meeting in 2028. Government leaders may want to consider how to increase the data that could be provided to CAEP in FY25, and whether community testing could inform a standard by FY26, which could also inform Mach cut-off certification. Options to do so might include front-loading U.S. community testing in FY24 and FY25, and conducting international tests in FY26 and FY27 to inform a CAEP standard during CAEP 14. Another option might be to supplement X-59 tests with more F-18 tests to provide more testing data earlier, using additional LBFD flights to validate that data or in other experiments.

The second critical output is supporting companies actively pursuing low-boom technology. Given that one major requirement of Lockheed's work on the X-59 is that the technologies and methodologies can be transitioned to other supersonic aircraft, such as commercial efforts, determining how to accelerate this support would be consistent with the project's goals. Examples of this might include providing technical information on environmental sensing capabilities for Mach cut-off flight or advanced LTO procedures.

B. LTO Noise

Industry and aircraft experts have acknowledged LTO noise as a significant hurdle to the successful development and implementation of supersonic aircraft. The regulations in place for subsonic aircraft are perceived as overly restrictive, and regulations for supersonic aircraft noise are not required until March 2020 (per the 2018 FAA Reauthorization Act). Both regulatory and technological efforts can address this challenge.[60]

1. Show International Leadership

The United States must show international leadership to ensure that its nascent supersonic industry can operate internationally, and thus have a better chance of commercially viability. The current FAA approach of setting an interim noise standard seems reasonable given company timelines contrasted with need to decrease regulatory uncertainty. However, a United States interim standard may not be sufficient to enable the international supersonic market, especially if the international community views the United States' efforts negatively. Showing a commitment to decreasing environmental effects, both immediately and especially over the long-term, would seem important to convincing fellow aviation states to support supersonic flight.

The FAA has been leading the efforts internationally and could possibly benefit from higher-level government support based on the outcome of the current study set to end in 2022. This leadership should ensure that LTO noise standards for supersonic are data driven and match the ICAO goals of producing standards that are technologically feasible, environmentally beneficial, and economically reasonable.

2. Ensure LTO Noise Standards and Regulations Account for the Differences between Subsonic and Supersonic Flight Regimes

The 2018 FAA Reauthorization Act requires that the FAA include supersonic aircraft in the applicability of LTO noise regulations by March 2020, and in doing so consider the "differences between subsonic and supersonic aircraft including differences in thrust requirements at equivalent gross weight, engine requirements, aerodynamic characteristics, operational characteristics, and other physical properties." These regulations must be economically reasonable and technologically feasible, as required by 49 U.S.C. § 44715.

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[60] In determining this standard, it is important to acknowledge that supersonic planes are likely not to be the noisiest aircraft at major airports: older, larger aircraft with more engines will likely be much louder than the 10-seat or even 50-seat supersonic aircraft under development. Appendix E offers a comparison of Boom's projected noise levels to those of existing aircraft.

The 2018 FAA Reauthorization Act is an important step in making regulations appropriate for supersonic aircraft, which will need to be implemented effectively by the FAA. Multiple interviewees shared this as an opportunity to account for the technical differences of supersonic aircraft, given that flight speed affects a number of other design and operation choices. Such a distinction would seem appropriate given the historical differentiation between planes of different weights, which is based on the physical realities of increased noise as a result of increased takeoff weight. Even if such a standard allowed supersonic aircraft to make more noise, an airliner such as Overture would still be quieter than most of its long-haul counterparts (see Appendix E).[61]

3. Support Noise Reduction Technologies in Supersonic Aircraft

Some technologies in government and company laboratories could be transferred to benefit civilian aircraft. Existing variable cycle engines (i.e., an engine with medium bypass at LTO and low bypass while cruising) have been identified by some companies pursuing supersonic aircraft as a major technology that could allow supersonic vehicles greater efficiency. The Federal Government could advance development of civil supersonic aircraft by supporting the transfer of these technologies from laboratory efforts (e.g., in the Air Force Research Laboratory and GE) to commercial production.

One example of a potentially transferrable propulsion technology is a so-called adaptive engine, such as the engines developed by both GE and Pratt & Whitney under the Air Force Research Laboratory's Adaptive Engine Technology Development (AETD) program. These engines are turbofans with an added third stream that changes geometry in flight (Ripple 2016). The result is a propulsion system that can be optimized for two or more flight modes; for instance, the engine can increase air bypass and thus efficiency when generating high thrust for takeoff and then decrease bypass for efficiency in level cruise. This could lead to a supersonic aircraft that uses less fuel overall, or that does not require an afterburner for takeoff or passing through the transonic regime. While technologies such as adaptive engines may lead to more efficient supersonic flight, the processes to transfer them from industrial R&D to commercial use will be both time consuming and expensive. It is most likely that such technology would only be incorporated into commercial aircraft after having been first developed for military applications, leveraging the resources of the Department of Defense (DoD) to support a full development effort. In the case of the AETD engines, they were indeed intended for

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[61] Establishing a permanent noise standard in the near term will be more useful for potential aircraft designers than an interim standard that is expected to be replaced; clear and steady regulatory standards give aircraft designers certainty and will allow them to take advantage of derivative designs rather than forcing another clean sheet design to account for new noise regulations. The FAA should also endeavor to solidify the new standards as quickly as possible; a predictable regulatory regime may enable companies to move forward with finalizing designs, especially for investing in novel engine technology.

military fighters and test articles performed well; however, DoD does not plan to actually acquire the engines in the foreseeable future, making their use in commercial aircraft even more speculative.

The government can continue to invest in R&D efforts that address development of engines and airframes that minimize aircraft noise beyond current NASA efforts focused on modelling. This funding can be used for research conducted within NASA centers and for extramural performers. In particular, this Federal funding would help instigate action in supersonic flight. Given the lack of regulatory and therefore economic certainty in this area, many industry entities are reluctant to invest internal resources.

4. Investigate Supersonic ATC Practices

Several supersonic aircraft manufacturers have proposed new takeoff and approach procedures that will limit LTO noise, helping to meet noise regulations. These new procedures introduce two findings that the FAA and the greater supersonic community should investigate.

First, the government and supersonic community should investigate the safety of proposed landing and takeoff procedures, both their inherent risk and risk in combination with established air traffic patterns. For example, steep approach typically requires greater pilot intervention and skill than a standard approach angle and introduces ATC complexity in managing multiple flight paths on final approach. These procedures should be examined for safety before they can be assumed practicable.

Second, current airport and airspace operations should not be assumed as the best procedures for a supersonic aircraft or mixed fleet. Although any new operations will require a safety assessment, they may enable safer supersonic operations with smaller environmental impacts. It should not be assumed that subsonic ATC practices should apply wholesale to supersonic aircraft.

C. Continue to Support Efforts for Supersonic Testing

NASA’s ARMD plays a crucial role in developing U.S. aeronautics capabilities, including its critical X-59 mission. Given that NASA and the companies pursuing supersonic aircraft expect NASA to provide testing support, NASA interviewees note that ARMD could be better supported through new, flight-line aircraft. Indeed, an interviewee noted that most of ARMD’s fleet has about 5 years of remaining flight time, which may not be able to support ongoing efforts in civilian supersonics. One interviewee suggested that Armstrong could maintain planes as ready reserve for the Air Force while using them to support flight-testing opportunities.

In recent proposed rulemaking, the FAA clarified the information and processes necessary for a company to apply to conduct a supersonic flight test over land. These changes, while useful, were largely cosmetic and organizational, and will ultimately not alleviate the challenge of completing a successful application. Much of that challenge will consist of identifying a test area and providing all of the necessary information for the FAA to make an environmental determination with the National Environmental Policy Act. At this time, the FAA may not be able to reduce this burden without a broader determination that overland supersonic flight is acceptable. NASA could support testing by providing established test areas for supersonic flight, potentially building on processes developed for, and lessons learned from, X-59 community testing.

6. Conclusions

OSTP asked STPI to assess the potential future of supersonic civilian aircraft, offering options that the Federal Government may consider, as appropriate, to support the reintroduction of commercial supersonic aircraft. The demonstrated abilities of these companies to achieve each of their technical and business goals vary widely; indeed, some company claims may be unrealistic given the current technical maturity and regulatory landscape. Technical challenges and maintenance needs will contribute to high development and operational costs, which will likely be substantial until the fleet grows. Navigating the regulatory and certification processes will also pose a challenge. Even if these goals are achieved, quantifying the demand for these jets remains a challenge, as discussed in Chapter 3. While some companies' efforts may be commercially viable in the short- to medium-term, they will still likely rely on further technical and regulatory development.

Based on company timelines and the critical path of commercial development, there appear to be two distinct generations of future supersonic aircraft, as detailed in Table 6. The first generation is characterized by current development efforts that may result in first generation aircraft from Boom and Aerion; these aircraft are based on derivative engine technology and may be able to take advantage of Mach cut-off flight but not boomless cruise. A second generation might consist of updated Boom and Aerion aircraft, as well as contributions from other companies such as Lockheed Martin and Gulfstream, characterized by low boom cruise, new engine designs, and other lessons from an initial design cycle.

Table 6. Potential Waves of Commercial Supersonic Aircraft

	First Generation	Second Generation
Example Aircraft	Boom's Overture; Aerion's AS2	Lockheed Martin's QSTA; Gulfstream; Aerion Generation 2; Boom Generation 2
Characteristics	Derivative engines and airframe designs; potential Mach cut-off flight	Clean sheet designs; boomless cruise
Regulatory Decisions	LTO noise; emissions; Mach cut-off	*LTO noise; *emissions; Boom noise

* Distinct from first generation aircraft, the second generation may include new engine designs, potentially resulting in different determination of economic and technical reasonableness

Supporting both near-term and more advanced technologies will require tradeoffs. Generation 1 may demonstrate the market and technology necessary for the investment in more advanced supersonic aircraft, but it could also limit future supersonic opportunities if it does not prove the economic viability of supersonic flight or if the environmental effects generate political pushback that prohibits future enterprises. The regulatory action required for generation 1 (e.g., Mach cut-off flight) may not apply to generation 2. Investments in the technologies for generation 2 (e.g., boomless cruise and new engine technologies) may support the future of supersonic flight while not sufficiently supporting the advances that are ready for implementation in the next 5 years. The government may want to incentivize the risks taken by the companies building first generation planes while accelerating the arrival of generation 2. Generation 2 aircraft may require more advanced technology, but they do not need to be long delayed or even deployed second.[62]

The United States is currently working on many of the challenges for both generations of aircraft, but may want to consider what efforts to prioritize based on some of the tradeoffs above. The government's primary effort in civilian supersonic flight is NASA's LBFD mission, which is both a technology demonstrator (using technologies such as airframe shaping to develop an aircraft with a sonic boom less than 75 PLdB) and an input to U.S. and international regulations. For first generation aircraft, however, NASA's LBFD mission is expected to yield little useful information—current aircraft efforts are advancing ahead of NASA timelines. However, two additional companies (Lockheed Martin and Spike) claim to be waiting on some aspects of design and development to accommodate information from the LBFD. Given the direct impacts of regulations on technical specifications of these aircraft and therefore the commercial viability of each effort, as well as ongoing U.S. Government regulatory actions, we compare the timelines of public and private regulatory and technical efforts in Figure 4.

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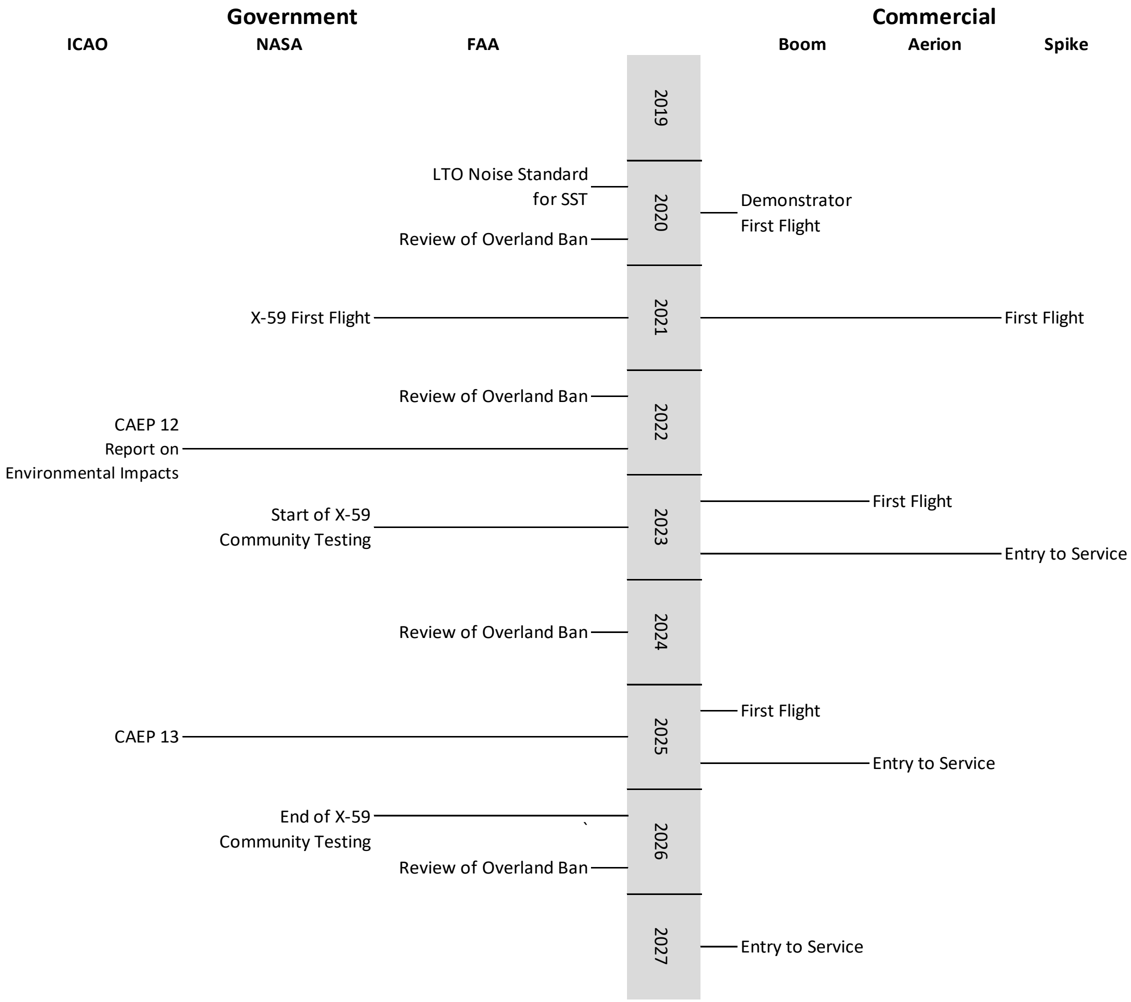
[62] This point is critical for environmental considerations. If the environmental effects of first generation designs are too great, the implementation of new research and technologies could still enable supersonic aircraft to be successful.



The timeline does not include Lockheed Martin's QSTA or any potential Gulfstream effort as details regarding these programs were not made available.

Figure 4. Timeline of Government and Private Supersonic Efforts

While the United States is moving quickly to address LTO noise regulations, the international community is on a much slower timeline. Furthermore, efforts to address parameters such as LTO noise and sonic boom require significant design choices that would likely be made well before first flight.

Other, second generation aircraft may be waiting on the results and lessons learned from LBFD, which currently may not be available until 2026, delaying development. Additionally, given that the LBFD mission's community testing begins in 2023 and will not end until 2026, it will only contribute limited information to the CAEP meetings in 2022 and 2025. Thus, information from the full testing mission will not be available until CAEP's meeting in 2028, years after the first aircraft are planned to enter service. Also, first generation aircraft may be able to implement Mach cut-off flight before LBFD would lead to an en route noise standard. Work on proving a regulatory pathway for Mach cut-off flight could enable companies to take advantage of supersonic flight over land in the near term.

Several companies are investing millions of dollars in the development of supersonic aircraft, with plans to deploy them within the next decade. The United States Government can take action to support the economic and technical viability of these aircraft by revisiting its regulations for the overland ban based on the potential for Mach cut-off flight and creating an appropriate LTO noise standard. An interim standard for generation 1 could incentivize early development while allowing future iterations to address environmental effects. Considerations of LTO noise should also include a thorough review of ATC processes that could minimize environmental effects while maintaining safe operation. Another area that could be crucial to the first generation of supersonic aircraft is enabling Mach cut-off flight; this could support commercial viability of these aircraft and would benefit from action from both NASA and FAA. In order for these endeavors to be successful, these efforts will need to be shared internationally.

The United States is already investing in the longer-term picture of supersonic flight through the LBFD mission. The realization of boomless cruise and the establishment of a reasonable noise standard will be critical to realizing the potential of supersonic flight.[63] However, one piece missing in the vision of supersonic flight will be addressing the development of engines for next generation supersonic aircraft. Catching up on the decades of R&D invested in subsonic engines and overcoming the fundamental challenges of achieving supersonic flight will require innovative and in-depth research; this has already begun on adaptive engines but will likely require additional investment and technology transfer from existing developments. Other research areas such as biofuels can help narrow the supersonic emissions gap while also forwarding subsonic efforts to reduce emissions. Generation 2 relies especially on the LBFD mission, which is acting both as a pathfinder for new technologies as well as the critical path for their implementation. An additional X-59 aircraft helps mitigate the risk of an aircraft failure that could delay the supersonic industry.

The U.S. Government thus has the opportunity to act in support of supersonic flight in the short- to medium-term, offering a predictable regulatory environment for these commercial efforts on their current schedule projections. Both the technical issues of supersonic flight and the uncertain regulatory environment pose challenges to companies

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[63] In accordance with this, an area critical to government influence is enabling responsible supersonic flight over land. Even if aircraft business cases can close with the ban in place, stakeholders agree that lifting this ban is key to enabling the long-term success of civil flight in this speed regime. The government could commit to using its biennial review of whether the ban on overland flight (section 91.817 of title 14, Code of Federal Regulations, and Appendix B of part 91 of title 14, Code of Federal Regulations) may be amended to determine, using information from company tests and NASA's X-59, an appropriate noise level for the sonic boom.

seeking to develop supersonic business jets and airliners. The U.S. has already taken important steps in supporting supersonic aircraft, both through R&D and in committing to update regulations through the 2018 FAA Reauthorization Act. However, U.S. companies are currently pursuing shorter timelines than those supported by governmental technical and regulatory efforts. The government can support the implementation of supersonic flight, demonstrating U.S. leadership in aviation and removing unnecessary burdens to innovation.

Appendix A.
Past Civilian Supersonic Efforts

The governments of the United States, United Kingdom, France, and Russia have each pursued civilian supersonic flight. In the United States, work on commercial supersonic aircraft began with small-scale studies in the early 1950s, less than a decade after the first military supersonic aircraft entered service (Horwitch 1982; Newhouse 1982; Heppenheimer 1995; Rodgers 1996; Conway 2005). The U.S. Government's own work in support of supersonic commercial aircraft has included several programs, each of which was ultimately hindered by a combination of political, technological, regulatory, and economic hurdles. Research on the impact of supersonic flight programs was conducted as part of Operation Bongo II, in which the Air Force flew its XB-70 aircraft at 65,000 feet over Oklahoma City in 1964. Those tests yielded a significant number of noise complaints as well as reports of broken glass and cracked plaster, fueling significant public concern over the effects of supersonic flight (Fields 1997; Benson 2013). The U.S. Government then funded the American SST program in the 1960s, in which Boeing was chosen to build a Mach 3 aircraft that could carry 300 passengers, designated the 2707. It was canceled in 1971 under considerable political pressure, due largely to program delays, concerns over environmental impact, and doubt in economic plausibility of the aircraft (McLean 1985). The U.S. Government's involvement in civilian supersonic flight was revived through NASA's High-Speed Research (HSR) program in the 1990s, which sought to develop an aircraft (the High-Speed Civil Transport [HSCT]) capable of traversing transpacific routes with 300 passengers at Mach 2.4. The program intended to make the HSCT possible within 20-25 years but was cancelled in FY 1999 due to resource constraints (Allen 2008).

The Concorde, a joint venture between France's Société Nationale Industrielle Aérospatiale and the British Aircraft Corporation, was used in regular commercial service for almost 27 years, primarily on transatlantic routes (Owen 1997, 2001; Glancey 2015). The Concorde was first flown in 1969 and operated commercially from 1976 until 2003. Initially, 16 companies preordered 78 Concorde aircraft. Ultimately, only 20 aircraft were manufactured; Air France and British Airways each purchased 7, and the others were used as prototype and test aircraft (BBC News 2000; Congressional Research Service 2018).

The Concorde used four Rolls-Royce/SNECMA Olympus 593 Mk 602 engines, each of which produced a thrust of 169,000 N.[1] These engines were designed to handle the very high inlet temperatures associated with supersonic flight, with high-temperature metals such as titanium and nickel superalloys used throughout. Though at the time of their design they were extremely efficient, the engines relied on the use of afterburners—extra combustors mounted just ahead of the nozzles, to provide the thrust required for takeoff and to push through the high drag of the transonic regime. These afterburners increased thrust (by about 17%) for takeoff and transition through transonic speeds (Benningfield 2007). The afterburners consumed significant fuel, added maintenance requirements, and contributed significantly to aircraft noise at takeoff. Because the engines had to operate across a range of Mach numbers (i.e., for LTO operations as well as maximum cruise speeds), both their inlets and nozzles had moving parts, adding weight and complexity. Additionally, the aircraft adjusted for supersonic trim changes by shifting fuel between tanks. The Concorde's inlets were especially complicated designs, and the Concorde became one of the first airplanes to have a digital control system just to manipulate its inlet (Page 1975).

Concorde fares were quite high compared to subsonic offerings: in 2003 a roundtrip ticket across the Atlantic on the Concorde cost £8,000 (about $16,100 in 2019 USD), while subsonic first-class tickets were only about half this amount (Glancey 2015). The aircraft was designed in the mid-1960s when oil was relatively inexpensive. However, because of its high rate of fuel burn, the Concorde was particularly susceptible to price increases (e.g., those caused by the Oil Crisis of 1973–1974). Demand for the Concorde decreased as global business travel shifted toward Asia, as the aircraft lacked the range necessary to travel from the U.S. or Europe to major Asian destinations.

The plane flew at more than twice the speed of sound, slightly above Mach 2.0 (1,350 miles per hour), crossing the Atlantic in less than four hours. It flew at an altitude of 60,000 feet with a range of 4,143 miles, and could carry up to 100 passengers (British Airways n.d.).[2] Some critics cited environmental concerns regarding the Concorde, including the risk of damaging the ozone layer at the aircraft's cruising altitude. Others problems with the craft included its relatively high rate of fuel consumption. a full Concorde flying from Paris to Washington, D.C. used 0.063 gallons per passenger-mile (16 miles per gallon per passenger), compared to the 0.020 gallons per passenger-mile of the Boeing 747 flown in 1976 (50 miles per gallon per passenger) (Flight International 1976). Additionally, the Concorde was riddled with expensive maintenance issues that moved the aircraft further

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[1] Although Rolls-Royce was instrumental in the supersonic flight of the Concorde, based on recent publications and our personal conversations the company does not seem to be in active development, instead tracking the market for potential opportunities.

[2] The Concorde had a wingspan of 83 feet, 18inches; length of 203 feet, 9 inches; height of 37 feet 1 inch; and takeoff weight of 408,000 pounds (British Airways n.d.).

from profitability (Flight International 2003). These costs were exacerbated by the small fleet size; since there were just 14 aircraft, each required specialized parts, labor, and crews (Glancey 2015).

The United States banned all commercial supersonic flight over land, largely due to the sonic boom (which extends at an angle from an aircraft and can follow the plane's path for many miles) that is created by an aircraft traveling in excess of the speed of sound, Mach 1 (Benson 2013).[3] This essentially limited the Concorde to flights between U.S. east coast cities and Western Europe, greatly restricting the U.S. customer base.[4] Further concerns over noise patterns on the ground led the United States to restrict service even in U.S. airports (Owen 1997).[5] This combination of regulatory restrictions, increasing costs (by the time of the Concorde's first flight it had already cost fifteen times more than original estimates; Gillman 1977), and the loss of an Air France Concorde in July 2000 from a disintegrating tire that led to a fuel tank rupture and subsequent accident ultimately steered British Airways and Air France to end the program (Flight International 2003).[6]

Russia's supersonic aircraft was likewise a commercial failure (Moon 1989). The design of the Tupolev Tu-144 was revealed at the 1965 Paris Air Show and a prototype made its first flight in December 1968, two months before that of the European aircraft (Owen 1997). The Tu-144 (nicknamed the "Concordski" for its obvious similarities to the Concorde) was designed to carry 140 passengers at Mach 2; it could reportedly reach Mach 2.4 (Simons 2012). It made 55 passenger flights but never demonstrated Concorde-level

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[3] Even before production of the Concorde, the FAA was granted authority to "prescribe and amend standards for the measurement of aircraft noise and sonic boom" and "…rules and regulations…necessary to provide for the control and abatement of aircraft noise and sonic boom" under the Aircraft Noise Abatement Act of 1968. In 1970, the FAA proposed a regulation that would restrict the operation of civil aircraft at speeds greater than Mach 1; this was finalized in March 1973 (14 CFR § 91.817 and 14 CFR Part 91, Appendix B).

[4] Specifications for aircraft determined an airline's permitted aircraft types, routes, and flight procedures. Though most requests for flights (i.e., those of Air France and British Airways in 1975 to each operate two flights to JFK and one to IAD daily) were automatically approved, the Concorde's engines were expected to be noisier and contribute more pollution than the airlines' subsonic aircraft; these concerns led to increased restrictions on the Concorde's flight opportunities to the U.S.

[5] The FAA did pass an regulation in 1978 that limited the noise of the Concorde is reduced to "the lowest levels that are economically reasonable, technologically practicable, and appropriate for the Concorde type design," rather than the quantitative levels that subsonic aircraft had to meet (14 CFR § 36.301).

[6] A Concorde was lost at Charles de Gaulle Airport in July 2000. At takeoff, the plane ran over a metal strip that had been dropped on the runway by another aircraft; the strip gouged a tire which sent a piece of rubber into the fuselage, which in turn ruptured a fuel tank. Spilling fuel was ignited, likely by contact with the hot engines (though possibly by a shorted wire in the landing gear bay). Two of the aircraft's engines surged, then lost power; one of those engines was shut down by the crew, and the remaining three engines were unable to deliver enough airspeed for the craft to remain airborne. A power surge in one of the affected engines banked the aircraft, and the pilots were unable to regain control. With the wing disintegrating under the heat of burning fuel, and loss of engine thrust, the aircraft became uncontrollable and crashed into a hotel near the airport.

reliability. Pilot error led to a particularly spectacular crash at the 1971 Paris Air Show. The aircraft never had solid customer base and eventually was used largely for airmail. Russia ceased production of the TU-144 in 1982, and the aircraft was withdrawn from service in 1984 due to unprofitability. The last TU-144 was actually used by NASA, during a series of flights in Russia as a joint U.S.-Russia testbed for studying supersonic acoustics (Owen 1997; Rivers 2010; NASA 2014).

The TU-144 was powered by several different engine types while in operation. The aircraft originally used Kuznetsov engines (starting with the NK-8 afterburning turbofan and changing to the NK-144 and later NK-144A) that offered disappointing performance, resulting in relatively short range for the aircraft. The Kolesov engine company later developed the RD-36-51A afterburning turbofan specifically for the TU-144. The final version of the plane operated by NASA for acoustic tests flew with military NK-321 engines because the Kolesov engines were no longer manufactured or maintainable. The last TU-144 was actually used by NASA, during a series of flights in Russia as a joint U.S.-Russia testbed for studying supersonic acoustics (Owen 1997; Rivers 2010; NASA 2014).

Appendix B.
Excerpt from the Federal Aviation Administration Reauthorization Act of 2018 (Pub. L. 115–254 Section 181)

SEC. 181. FAA LEADERSHIP ON CIVIL SUPERSONIC AIRCRAFT.

(a) In General.—The Administrator of the Federal Aviation Administration shall exercise leadership in the creation of Federal and international policies, regulations, and standards relating to the certification and safe and efficient operation of civil supersonic aircraft.

(b) Exercise Of Leadership.—In carrying out subsection (a), the Administrator shall—

(1) consider the needs of the aerospace industry and other stakeholders when creating policies, regulations, and standards that enable the safe commercial deployment of civil supersonic aircraft technology and the safe and efficient operation of civil supersonic aircraft; and

(2) obtain the input of aerospace industry stakeholders regarding—

(A) the appropriate regulatory framework and timeline for permitting the safe and efficient operation of civil supersonic aircraft within United States airspace, including updating or modifying existing regulations on such operation;

(B) issues related to standards and regulations for the type certification and safe operation of civil supersonic aircraft, including noise certification, including—

(i) the operational differences between subsonic aircraft and supersonic aircraft;

(ii) costs and benefits associated with landing and takeoff noise requirements for civil supersonic aircraft, including impacts on aircraft emissions;

(iii) public and economic benefits of the operation of civil supersonic aircraft and associated aerospace industry activity; and

(iv) challenges relating to ensuring that standards and regulations aimed at relieving and protecting the public health and welfare from aircraft noise and sonic booms are economically reasonable, technologically practicable, and appropriate for civil supersonic aircraft; and

(C) other issues identified by the Administrator or the aerospace industry that must be addressed to enable the safe commercial deployment and safe and efficient operation of civil supersonic aircraft.

(c) International Leadership.—The Administrator, in the appropriate international forums, shall take actions that—

(1) demonstrate global leadership under subsection (a);

(2) address the needs of the aerospace industry identified under subsection (b); and

(3) protect the public health and welfare.

(d) Report To Congress.—Not later than 1 year after the date of enactment of this Act, the Administrator shall submit to the appropriate committees of Congress a report detailing—

(1) the Administrator's actions to exercise leadership in the creation of Federal and international policies, regulations, and standards relating to the certification and safe and efficient operation of civil supersonic aircraft;

(2) planned, proposed, and anticipated actions to update or modify existing policies and regulations related to civil supersonic aircraft, including those identified as a result of industry consultation and feedback; and

(3) a timeline for any actions to be taken to update or modify existing policies and regulations related to civil supersonic aircraft.

(e) Long-Term Regulatory Reform.—

(1) NOISE STANDARDS.—Not later than March 31, 2020, the Administrator shall issue a notice of proposed rulemaking to revise part 36 of title 14, Code of Federal Regulations, to include supersonic aircraft in the applicability of such part. The proposed rule shall include necessary definitions, noise standards for landing and takeoff, and noise test requirements that would apply to a civil supersonic aircraft.

(2) SPECIAL FLIGHT AUTHORIZATIONS.—Not later than December 31, 2019, the Administrator shall issue a notice of proposed rulemaking to revise appendix B of part 91 of title 14, Code of Federal Regulations, to modernize the application process for a person applying to operate a civil aircraft at supersonic speeds for the purposes stated in that rule.

(f) Near-Term Certification Of Supersonic Civil Aircraft.—

(1) IN GENERAL.—If a person submits an application requesting type certification of a civil supersonic aircraft pursuant to part 21 of title 14, Code of Federal Regulations, before the Administrator promulgates a final rule amending part 36 of title 14, Code of Federal Regulations, in accordance with subsection (e)(1), the Administrator shall, not later

than 18 months after having received such application, issue a notice of proposed rulemaking applicable solely for the type certification, inclusive of the aircraft engines, of the supersonic aircraft design for which such application was made.

(2) CONTENTS.—A notice of proposed rulemaking described in paragraph (1) shall—

(A) address safe operation of the aircraft type, including development and flight testing prior to type certification;

(B) address manufacturing of the aircraft;

(C) address continuing airworthiness of the aircraft;

(D) specify landing and takeoff noise standards for that aircraft type that the Administrator considers appropriate, practicable, and consistent with section 44715 of title 49, United States Code; and

(E) consider differences between subsonic and supersonic aircraft including differences in thrust requirements at equivalent gross weight, engine requirements, aerodynamic characteristics, operational characteristics, and other physical properties.

(3) NOISE AND PERFORMANCE DATA.—The requirement of the Administrator to issue a notice of proposed rulemaking under paragraph (1) shall apply only if an application contains sufficient aircraft noise and performance data as the Administrator finds necessary to determine appropriate noise standards and operating limitations for the aircraft type consistent with section 44715 of title 49, United States Code.

(4) FINAL RULE.—Not later than 18 months after the end of the public comment period provided in the notice of proposed rulemaking required under paragraph (1), the Administrator shall publish in the Federal Register a final rule applying solely to the aircraft model submitted for type certification.

(5) REVIEW OF RULES OF CIVIL SUPERSONIC FLIGHTS.—Beginning December 31, 2020, and every 2 years thereafter, the Administrator shall review available aircraft noise and performance data, and consult with heads of appropriate Federal agencies, to determine whether section 91.817 of title 14, Code of Federal Regulations, and Appendix B of part 91 of title 14, Code of Federal Regulations, may be amended, consistent with section 44715 of title 49, United States Code, to permit supersonic flight of civil aircraft over land in the United States.

(6) IMPLEMENTATION OF NOISE STANDARDS.—The portion of the regulation issued by the Administrator of the Federal Aviation Administration titled “Revision of General Operating and Flight Rules” and published in the Federal Register on August 18, 1989 (54 Fed. Reg. 34284) that restricts operation of civil aircraft at a true flight Mach number greater than 1 shall have no force or effect beginning on the date on which the

Administrator publishes in the Federal Register a final rule specifying sonic boom noise standards for civil supersonic aircraft.

Appendix C.
Interviewee Affiliations

Aerion
U.S. Air Force
Boom
EU Commission
FAA
FlexJet
General Electric
Gulfstream
Hogan Lovells
Information Technology Information Foundation
Japan Airlines
Lockheed Martin
NASA
Rolls Royce
Spike Aerospace
Teal Group
World Bank

Appendix D.
Case Studies of Commercial Supersonic Efforts

This section offers detailed case studies on each company considered in this report. This information is largely based on interviews with representatives of the companies discussed here and their partners. A summary of this information, including an assessment of the viability of these efforts, is offered in Chapter 4.

Lockheed Martin

In June 2019, Lockheed Martin shared its design for a Quiet Supersonic Technology Airliner (QSTA), a twin-engined aircraft that is expected to carry 40 passengers at Mach 1.8 (Neild 2019).

Business Case

- Lockheed Martin has not yet publicly shared business plans for the QSTA.

Technology Development

- The design builds on NASA's demonstration plane, the X-59 (discussed in Chapter 4), which is under development in Lockheed Martin's Skunk Works Division; the team hopes the X-59 will help prove many of the technologies necessary for the QSTA. One such technology is the shaping of the aircraft, through which the team expects to minimize the sonic boom, reducing it to a "thump" similar to a car door slamming.
- The QSTA will allow pilot vision through forward visibility systems, and laminar flow wings will allow increased range and reduced emissions.
- The plane will likely require a novel engine; the company's announcement stated it will be medium-bypass and non-afterburning, with 40,000 pounds of thrust. However, a representative claims that existing engine concepts could potentially be adapted for this aircraft (e.g., through a new low-pressure spool, new fan, and new low-pressure turbine).

Regulatory Status

- The team notes that the information from the X-59 program will be crucial in addressing regulatory issues regarding supersonic flight, which will allow the aircraft to fly numerous routes.

- Given the need for regulatory movement, there is no timeline on when the QSTA will be produced.

Boom Technology

Denver-based startup Boom Technology is developing a Mach 2.2 airliner, Overture, with commercial service beginning in the mid-2020s. The 55-passenger aircraft will have a range of 4,500 nautical miles and fly at an altitude of up to 60,000 feet.[1]

Business Case

- The company posts Overture's sale price at $200 M and estimates the market at 1,000–2,000 planes in its first 10 years of production. Boom estimates that development and certification of Overture will cost $6 billion (Warwick 2019a).[2]
    - Boom's current business case does not require supersonic flight over land, and Overture will fly over the United States at speeds lower than Mach 1 as necessary;[3] however, the company estimates that its market would increase by 70% if the ban on supersonic flight over the United States were lifted.[4]
- Based on internal analyses and estimates that fares on Overture will be comparable to those of subsonic business class seats, Boom considers Overture "meaningfully less costly to operate" than subsonic wide-body aircraft.
- Boom expects to expand its 100-person workforce to about 500 during the design period and scale up for production to 1,000-2,000 manufacturing employees.

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[1] Based on the paths flown by subsonic aircraft, this 4,500 nm range would allow Overture flights to Europe from much of the United States (e.g., New York to Paris or Dallas to London) but flights from Los Angeles would not be able to reach the majority of Asia without a fuel stop.

[2] The company has so far raised over $141 M, most recently in a $100 M Series B venture. Investors include a number of U.S.-based venture capital firms along with several international funds such as a Chinese travel service Ctrip.com (Pitchbook 2019a). Virgin Group has also preordered 10 aircraft.

[3] However, the company is considering polar options that would allow for faster speeds (e.g., corridors over Canada, Russia, Greenland), and is also interested in Mach cut-off flight.

[4] Boom's early analyses of routes that could potentially support supersonic airliners (based on demand, practicality, and international regulations) indicate a strong market for supersonic airliners; the company asserts the potential for Overture to service over 500 routes (even without overland supersonic flight. For example, Boom's analysis shows that global airlines fly 1,800 lie-flat seats each way, every day between New York and London; based on the company's estimate for flight frequency, 15 Overture aircraft could replace these seats. Another example they offer is the San Francisco to Tokyo route, which would allow an individual to leave California mid-morning Sunday, land five hours later, and return to San Francisco Monday night.

- Boom expects airlines to view Overture as an opportunity to differentiate themselves from competitors. Boom's website notes the possibility of a "halo effect"; travelers may even select the airline for subsonic flights, intending to accumulate miles and build loyalty status with an airline that offers the possibility of flying supersonic.

Technology Development

- Overture's website says the engine will use three non-afterburning turbofan engines (Boom 2019). Boom's CEO stated at the 2019 Paris Air Show that the company is involved in an "iterative process" with multiple potential engine suppliers.
  - As of early 2019, the team was in conversation with three companies, which are reportedly self-funding the research; company presentations suggest that the company remains open to both a derivative engine and a clean-sheet design (Miller 2019).[5]
  - The company expects the fuel burn per seat-mile to be comparable to that of current subsonic business class.[6] Representatives note the importance of the thrust-specific fuel consumption (TSFC) of the aircraft and claim the company is considering such features as time between overhaul (given that the engine is running hot most of the time), low fuel burn, and duration of core life.
- Overture is expected to use composite materials and the same delta wing configuration used by the Concorde. The engine is not expected to rely on afterburners. The company cites technical advancements that have only recently been accepted by the FAA for use on commercial aircraft (e.g., composite fuselage, high-temperature material systems) as enabling the design. Boom is developing supersonic aero-acoustic analysis capability in-house.
  - The company claims that NASA's work on low-boom designs (i.e., the X-59) does not align with the timeline of Overture's development.

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[5] Boom noted that the company could benefit from increased industry and government attention to variable cycle engines (i.e., an engine with medium bypass at LTO and low bypass while cruising, as well as more efficient engines and propulsion solutions) and indicated that R&D efforts could be transitioned for civilian supersonic flight (e.g., those on variable cycle engines for military use by GE and Pratt and Whitney). The company is using several proprietary tools developed internally or used in collaboration with NASA to prepare the design for other situations enabled by ongoing technological advances (e.g., no pilot, or pilot on the ground).

[6] Fuel consumption of subsonic aircraft flying medium- to long-haul routes ranges from about 0.014–0.1 gallons of fuel per seat mile.

- Routes over the Pacific will likely require a refueling stop (see Chapter 3, Table 2); company leadership expects the stop will take less than an hour and passengers will not have to deplane.
- Boom is pursuing Mach cut-off flight, which representatives assert is not being prioritized by the FAA or ICAO. Company representatives note that this capability will affect a number of aspects of the aircraft including avionics and data inputs.
- Boom's two-seat demonstrator, XB-1, will fly at Mach 2.2 and is intended to show that the company can build a supersonic aircraft. Design and construction of XB-1 began in early 2019; the team plans to finish assembly in December 2019 and begin flights in 2020.
  - The plane is a one-third scale model of the Overture and is expected to be a relatively small test program (i.e., the plane will not be certified). XB-1 will use off-the-shelf technology in the GE J85-15, modified by Boom to fly at Mach 2.2.[7]
  - XB-1 will prove some of the key technologies for Overture (e.g., advanced carbon fiber composites, a refined delta wing, and an efficient variable-geometry propulsion system). Representatives hope it will also demonstrate the demand for supersonic aircraft and spur investment and R&D efforts.

Regulatory Status

- Boom is expecting to reach LTO noise levels between those required by the current subsonic Stage 4 and Stage 5 requirements for the aircraft;[8] company representatives claim Overture cannot meet Stage 5 requirements without what they consider major reductions in performance.
  - Appendix E offers a comparison of Boom's target LTO noise level to that of the current fleet servicing major airports as well as a specific comparison to aircraft frequenting Boom's targeted routes.
- Representatives hope to set the precedent that Mach number (which directly affects much of the physics of the aircraft) will be considered in LTO noise

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[7] Boom has entered a partnership with Prometheus Fuels, which will supply carbon-neutral fuel for XB-1. Prometheus hopes to develop technology to extract carbon dioxide from the air and repurposes it into the fuel supply, working toward a fully renewable fuel supply (Miller 2019). The company's website offers limited information, and the project seems to be in its early stages (https://www.prometheusfuels.com/).

[8] In designing an aircraft with LTO noise that will not meet current requirements, the company assumes that U.S. and international regulators will agree on an alternative standard for supersonic aircraft and that this regulation will be somewhat more attainable than the current subsonic noise standards.

regulations, (potentially alongside current factors such as the number of engines and weight of the aircraft).

- Representatives expect Overture will be able to operate in existing airport and air traffic systems without major issue, and be compatible with current ground support equipment and processes; however, they do note that some activities will require Air Traffic Control approval and accommodation. For example, the company plans to certify Overture for steep approaches (e.g., 5-6 degrees) to reduce landing noise. The company is working with the FAA on additional regulations related to airport operations (e.g., allowing reclined seats during LTO, which has received initial FAA support).
- Overture's test process will include six aircraft logging thousands of hours of service before delivery to airlines (Miller 2019).
  - Boom's representative noted specifically that some aspects of the General Operating and Flight Rules (14 CFR Part 91) are not sufficiently supportive for the company to conduct production flight tests (discussed in Chapter 2B).
  - A representative noted there is currently no legislation to establish a new supersonic corridor, though some states may be interested in a supersonic testing tunnel.

Partnerships

Japan Airlines

- Japan Airlines (JAL) invested in Boom in late 2017, with an option to buy up to 20 aircraft. JAL expects to introduce supersonic aircraft to routes that are frequently traveled for both business and leisure, such as those connecting Tokyo to Singapore, Honolulu, and Los Angeles; it should be noted that none of these routes involves supersonic flight over land. A representative expects to offer supersonic service on Overture alongside current subsonic options.
- JAL shares Boom's expectation that Overture's fares will be comparable to those in subsonic business class; a representative said the airline is still analyzing how this offering will affect subsonic demand and did not offer information on the issue of cross-subsidy. A representative indicated that JAL will likely offer all seats on Boom's aircraft at the economy level, forgoing any business or first class designations and maximizing the number of seats.
- While the Airline has not yet determined how it will manage aircraft operations, representatives expect JAL to conduct maintenance of the planes in-house, as is JAL's practice with subsonic aircraft.

- The two companies are collaborating regarding aircraft development, including discussions regarding network systems and engineering and leveraging the Airline's experience regarding safety and validation as well as onboarding and integrating systems with multiple new technologies. Additionally, JAL will work with Boom on developing and procuring its expectations for the cabin (e.g., galley and seat layouts).
- A JAL representative shared that at the February 2019 ICAO CAEP meeting, Japan maintained a neutral position on supersonic flight over land. However, individuals from JAL were confident that data-driven processes and sufficient analysis could support ICAO in establishing regulations that allow supersonic flight. The representative was optimistic that Japan would then accommodate the new or updated rules.

Additional Partners

- Boom has agreements with suppliers for other GE for engines on its demonstrator, Honeywell for instrumentation, and Netherlands-based TenCate Advanced Composites for leading edge materials (Ajmera 2017), as well as JPA Design and Stratasys (Miller 2019).

Aerion

Aerion expects to fly its 8–12 passenger AS2 business jet in 2023 and to enter service in 2025. The AS2 will fly Mach 0.95 over land and Mach 1.4 over ocean. Its range will be between 4,700 and 5,300 nm, depending on its flight speed.[9]

Business Case

- A company representative estimated the development cost of the AS2 at about $4 billion. The company expects to sell 500 to 600 AS2 aircraft in the next 20 years (300 in the first 10-year period the jet is available).
- The target customers for the $120 million AS2 are high net-worth individuals and companies, including those that already have a top-tier jet (e.g., Gulfstream G650). Aerion's analyses regarding business travel (considering the time of these trips, and the average cost of both employee time and the travel itself) indicate that entities in the market for business jets would pay a premium for even a small reduction in travel time.

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[9] The AS2's range for a full flight at Mach 0.95 is 5,300 nm, and its range for a full flight at Mach 1.4 is 4,700 nm.

- Aerion plans to keep the maintenance and support in-house and expects to employ 800–1,000 individuals while building the jet.

Technology Development

- Aerion's decision to target Mach 1.4 is driven largely by technology. Company analysis showed that a Mach 1.4 engine would get 2,000 hours of flight time, while a Mach 1.6 engine would get only about 500 hours (mostly due to the higher temperature); GE and Aerion therefore agreed to target speeds of Mach 1.4 to minimize engine change-outs. As aircraft speed approaches Mach 1.6–1.7, the build-up of heat requires different materials; these exotic materials drive the cost of the aircraft up quickly. This is compounded by increased fuel burn. Aerion representatives expect the supersonic engine to burn about 1.9 times the amount of fuel of subsonic engines, further increasing costs. Aircraft flying at higher Mach numbers will likely not have the endurance to take advantage of their faster speeds (e.g., an aircraft that can fly Mach 2.5 may only have a maximum flight time of 3 hours and will be unable to take full advantage of the time benefits of the increased cruise speed).
- The Aerion team anticipates that the technologies necessary for Mach cut-off flight will be ready for implementation on the aircraft in the 2025–2026 timeframe.[10] Aerion and The Pennsylvania State University have been funding research into Acoustical Modelling of Mach Cut-off Flight;[11] Aerion is providing cost-share in-kind matching funds, and the period of performance for this research ends December 31, 2019. The team has found that atmospheric conditions can have a significant impact the ability to maintain Mach cut-off flight; as a result, the ability to assess the atmosphere accurately and quickly will be crucial in avoiding ground booms.

Regulatory Status

- The AS2 is designed to meet Stage 5 LTO noise requirements, though GE representatives expressed some concern over this possibility. The wings and fuselage in particular were designed with the goal of reflecting noise to the ground. Aerion has shared computational data regarding environmental expectations with the FAA. While GE has not yet completed the analysis

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[10] Aerion promotes its "BOOMLESS CRUISE" capability, which will be possible at speeds approaching Mach 1.2 under certain temperature and wind conditions.

[11] This effort is funded under FAA Award Number: 13-C-AJFE-PSU, Amendments 20, 33, and 42 (ASCENT 2019).

regarding feasible LTO noise in the AS2, the company estimates that its LTO noise could be 1.3–1.5 times louder than that of comparable subsonic aircraft.

- The AS2 is not expected to incorporate technology from NASA's X-59 (discussed in Chapter 4A) due to the delayed timeline of NASA's demonstrator (Norris 2018).
- Aerion plans to work with Edwards Air Force Base Flight Test Center and NASA Armstrong Flight Research Center, with their first test data expected in 2022. A regimented flight test program is scheduled to begin in the third quarter of 2023, and AS2 is scheduled to make its first transatlantic flight on October 24, 2023, the 20-year anniversary of Concorde's last flight. The flight test program includes five test aircraft, each of which will test different aspects (e.g., environmental features, temperature); one of the five test aircraft will conduct all of its test using synthetic paraffinic kerosene, a biofuel from Los Angeles. Testing efforts initially made use of Lockheed Martin's wind tunnels, but the company is now using Boeing's facilities as part of their agreement.

Partnerships

Boeing

- On February 5, 2019, Boeing announced its partnership with Aerion, including a significant investment, though details were not disclosed. Boeing took a minority stake in the company and is providing engineering, manufacturing, and test flight resources, as well as "strategic vertical content," according to the company's announcement (Boeing 2019b). The goal of the investment is "to accelerate technology development and aircraft design."

General Electric

- General Electric (GE) is working to develop a family of supersonic engines to support the AS2 and potential future Aerion aircraft, known as the Affinity series.
- The company expects a market for 300–500 AS2 aircraft in the 10-year period following its certification (2025–2035); this market estimate is consistent with that of Aerion. The development of the engine is expected to cost Aerion about $1.2 billion.
- While the Affinity engine is being funded through private and commercial sources at this point, details were not offered regarding the arrangement of funding and how much, if any, is an internal investment from GE.
- The engine uses a commercial CFM56 core and builds on GE's experience developing supersonic engines for military use. The Affinity features many new

components, including a smaller fan, new booster, exhaust system, low-pressure turbine, and pressure system; it uses a supersonic inlet with a variable inlet guide vane and medium bypass ratio. Because the AS2 will need to support both transonic and supersonic flight, the core will run at a high power-level for cruise. The exact configuration of the low-pressure turbine is still under development, but the exhaust system is expected to be a moveable plug, which allows the system to change the area required for flights at different speeds.

- Given the core's commercial heritage and GE's extensive experience in exhaust systems and demonstrations, these components are estimated to be at a technology readiness level (TRL) of 6. The fan and low pressure turbine will be new and are estimated to be at TRL 3. GE's schedule currently matches that of Aerion: flight in 2023 and certification in 2025.
- GE is leveraging its experience in subsonic engines to develop the Affinity family (e.g., many aspects of flight are modeled through computational fluid dynamics analysis that can be applied to subsonic and supersonic conditions, and some aspects of subsonic engine development, such as the ability to suppress noise with liners) can be leveraged for supersonic flight. GE representatives hope to leverage advances in additive manufacturing for aviation to manufacture liners with unique passages that could help lower engine noise.
- The engine is certified for 100% ethanol fuel. The team expects that certifying every engine of every fleet for every biofuel will be a challenge, but notes the possibility of certifying in batches based on similarities.

FlexJet

- In 2015, FlexJet agreed to purchase 20 of Aerion's initial aircraft. Interest is based on the AS2's practical cabin, minimal need for regulatory change, and expected capability for Mach cruise over land.
- The company estimates that each aircraft will likely require an additional 10–12 employees, including about five pilots per plane.
- FlexJet representatives serve on the maintenance committee of the AS2, helping design the aircraft's interior and contributing to the maintenance schedule.[12]
- A FlexJet representative noted that that some aspects of the Tax Cuts and Jobs Act of 2017 might negatively affect the demand for business jets, given

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[12] The team is optimistic that Boeing's involvement will support the development of an aircraft that is relatively easy to maintain, given that Boeing designs are generally for high-use commercial airlines that fly 3,000 hours per year, rather than the 300–500 hours of typical business jets.

restrictions on opportunities to write off use of these planes. Under the Act, employees are no longer permitted to write off business entertainment expenses, and employees cannot write-off the non-reimbursed use of a private plane.[13]

Spike Aerospace

Spike Aerospace has announced plans for its S-512, an 18-passenger low-boom, Mach 1.6 business jet. The company expects the S-512 to fly at an altitude of 50,000 feet with a range of 6,200 nautical miles.

Business Case

- The company's business case relies on supersonic overland flight.
- The company expects to sell 500–850 S-512 jets over the first 10 years at $125 million each. Company studies (which include analyses of flight routes taken by the 4 billion global passengers in 2017 and consider distances travelled, and cabin class occupied) estimate that over 650 million passengers flew non-stop international flights between 2,000 and 7,000 miles long in 2017. Business and first class passengers totaled 72 million (11.2%) of those seats, a number that is projected to grow over the next decade (Prokopovic 2018). As a result, the company estimates that the S-512 could ultimately service a market of more than 13 million passengers each year.
- A representative from Spike expects that operating costs will be comparable to those of other business jets, potentially including a 15% premium.
- The company is targeting high net-worth individuals and companies and sees the potential to serve U.S. government needs for fast travel (e.g., in diplomatic or emergency events).
- Spike plans to use the S-512 to prove the technology and market before developing a less expensive jet.

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[13] This concern was connected to possible reduction in the demand for supersonic business jets: an executive accountable to the company at all hours can no longer write-off use of the business jet for a personal trip from which they may need to return, for business purposes, at any time. While some have claimed the Act is already impacting the market and may affect the use of and interest in supersonic business jets, other commentaries have noted that overall, the Act has had positive impact on the aviation market. See for example Bean (2018) and Perez and Van Geffen (2018).

Technology Development

- Spike's team expects the aircraft to be about 115,000 pounds at takeoff and 134 feet long.
- Though Spike has not built any hardware[14] and all noise estimates are based on computational analyses, a representative cited sonic boom as a challenge moving forward. The company is planning to shape the aircraft's wings to keep the boom at about 75 PLdB. Their targeted technology is referred to on the website as "patent-pending Quiet Supersonic flight technology," though details have not been shared.
- While the company has not announced selection of an engine, its website claims the S-512 will use two engines, each with thrust of 20,000 pound-force, or 88.9 kN (Spike 2018). Additionally, a representative claimed that some engineering considerations are awaiting information from the NASA X-59 demonstration project.
- A representative claimed that some engineering considerations are awaiting the outcome from the NASA X-59 demonstrator aircraft. Indeed, the website notes that the aircraft's design "continues to be improved upon" based on further analysis.
- The company's website notes that the S-512 eliminates traditional windows, increasing aircraft strength while limiting noise heard within the cabin. The website claims that the cabin will offer full-sized screens that can be programmed to project content from passengers' devices and can also show the aircraft's real-time surroundings.

Regulatory Status

- Spike's representatives claim the S-512 will comply with Stage 5 LTO noise regulations, though the company has not shared details regarding its efforts to achieve this.
- The representative estimates that it will be at least 10–15 years before U.S. regulations develop to enable supersonic flight; therefore, Spike is initially focusing on customers in Europe and the Middle East. The representative claimed that current global regulations will allow the company to operate its initial target routes between London and the Middle East, Hong Kong, and Dubai.

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[14] The company flew a "subsonic subscale" demonstrator in October 2017 to validate "design and aerodynamics," though details were not made available.

- The company plans to flight test the aircraft in California's Mojave Desert. The manufacturing location has not been selected, though some sources suggest Spike has considered numerous areas in Washington, including Spokane.

Partnerships

- At the January 2019 Global Investment in Aviation Summit in Dubai, Spike Chief Executive Officer Vik Kachoria claimed that Spike already has two orders for the S-512, though he did not offer additional details. He also indicated that the company is involved in ongoing discussions with a commercial airline regarding the potential development of a supersonic airliner.

Gulfstream

Gulfstream has extensive experience in civil supersonic research.[15]

Business Case

- A representative is confident that the market will support the demand for a supersonic business jet, even with the overland ban in place; this is based on purchases from both current jet-buyers as well as future potential customers and market studies conducted by Gulfstream over the last several decades.
    - Anecdotally, Gulfstream's customers are interested in offerings with higher speed capabilities. According to one representative, customers claimed that they flew the G650 (which has long-range cruise at Mach 0.85 and high speeds at Mach 0.925) for a year on the same routes they flew the G550 (long-range cruise at Mach 0.8) and saved nearly 50 hours of flight time and used less fuel.
    - Representatives note that lifting the ban would significantly improve the business case for a supersonic business jet.

Technology Development

- Technical details of any current jet effort were not shared, though a representative noted that product aircraft shape and size would likely be similar to current Gulfstream offerings (e.g., vision systems, symmetry flight deck).

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[15] Gulfstream has contributed to and developed technologies for aviation in advance of commercial airliners, and was involved in the Defense Advanced Research Projects Agency (DARPA) Quiet Supersonic Platform (QSP) program in the early 2000s. For example, the company was instrumental in bringing enhanced vision systems from military to civil applications via research in infrared cameras and piping that into the cockpit in the late 1990s. More recently, the company implemented active control sidesticks and touch screen controllers into its latest flight decks.

Regulatory Status

- Specific information regarding the company's expectations for LTO noise and the volume of the sonic boom was not shared.

Appendix E.
Noise Comparison of Boom's Overture Aircraft

The FAA Reauthorization Act of 2018 instructs the FAA to establish LTO noise regulations for supersonic aircraft by March 31, 2020. However, companies are already designing their aircraft in absence of these guidelines. Boom is not expecting its 55-passenger, three-engined supersonic airliner, Overture, to meet current Stage 5 restrictions;[1] the company instead expects Overture to produce a cumulative noise level between the volumes required by existing Stage 4 and 5 regulations for an aircraft of its size.[2] Boom argues that the current regulations would impose major technological design restrictions and claims that the company's current noise goal would not contribute significantly to the noise of the current fleet. However, many others have claimed that Overture's failure to meet existing noise regulations would contribute negatively to overall airport and fleet noise. To determine the impact of this noise level on current airport noise, we compare this projection to the noise levels of the aircraft servicing Dulles International Airport (IAD) and the long-haul aircraft that Overture will likely fly alongside or replace on transpacific and transatlantic routes.

Estimating the Noise of Overture and Other Aircraft

Boom representatives have claimed that Overture's cumulative noise level will be mid-way between the applicable levels imposed by current Stage 4 and 5 noise requirements. The noise levels permitted for this aircraft under each stage are shown in Table 4; we calculate these values using FAA standards (14 CFR Part 36, Appendix B), assuming Overture will use three engines (per Boom's website) and have a takeoff weight of 77,100 kg (Flight Global 2017). If the aircraft's noise is mid-way between Stage 4 and 5 requirements, as projected, Overture will have a cumulative noise (i.e., the sum of TO, APP, and Flyover noise) of 278.8 effective perceived noise in decibels (EPNdB).

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[1] Representatives from Aerion and Spike claim their business jets (the AS2 and S-512, respectively) will be compliant with the existing Stage 5 noise regulations for subsonic aircraft. However, technical experts involved in these projects recognize that meeting these will be a challenge.

[2] Representatives assert that the noise at each point—takeoff (TO), approach (APP), and flyover—will be at least 1 dB below the specific Stage 3 requirement for each point, satisfying this parameter of the Stage 5 regulation. Stage 4 did not require a reduction at any of the three points, only a reduction in cumulative noise of 10 dB.

Table E-1. Noise Requirements for 3-Engine Plane Weighing 77,100 kg (in EPNdB)

	TO	APP	Flyover	Total
Stage 3	96.2	100.66	94.72	292.30
Stage 4	N/A	N/A	N/A	282.30
Stage 5	95.2	99.6	93.72	275.30

For each aircraft type, we use data provided by certification authorities and maintained in the Noise database (NoisedB) under the aegis of ICAO. NoisedB offers data for 89% of the types of aircraft servicing Dulles and 100% of the aircraft types considered for the long-haul comparison. An example data point is shown in Table E-2.

Table E-2. Sample Noise Data Entry

Aircraft Type	Mass (1000 kg)	Stage	TO	APP	Flyover	Cumulative
A319	70	4	91.40	93.60	85.1	270.10

IAD Comparison

To compare the expected noise level of Overture to current airport noise, we chose the fleet servicing Dulles International Airport (IAD) in 2017; this dataset offers an example of the current aircraft fleet, which includes regular service from business jets to wide body aircraft. Of the aircraft servicing IAD in 2017, 55% were categorized as Stage 3 and 45% were categorized as Stage 4. Because the Stage 5 regulation went into effect on December 31, 2017, no aircraft in service in 2017 was categorized as Stage 5.[3] However, a majority (64%) of these aircraft types (52% of those in Stage 3 and 80% of those in Stage 4) would meet Stage 5 requirements if they were to be certified today. We can compare the Overture noise estimates with the use-frequency of the entire fleet as shown in Table E-3.

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[3] An aircraft is categorized based on the standard it met when entering into service. Aircraft entering service that met Stage 3 standards would remain classified as a Stage 3 aircraft, even if it would satisfy the noise levels set by future requirements (i.e., after the Stage 4 requirement was introduced, the aircraft would not be re-categorized to Stage 4, even if its noise levels were below those required by the Stage 4 regulations).

Table E-3. Comparison of Overture to Percent of Flights Servicing IAD in 2017

Scenario	Percent of Flights Quieter than Overture
Stage 4	80.4%
Midway Point	80.4%
Stage 5	71.4%

Figure E-1 compares the noise of Overture to that of each aircraft servicing IAD in 2017. Overture would be louder than the aircraft offering about 80% of the flights servicing Dulles. This large difference may be expected, as Overture's takeoff mass is larger than those of the aircraft making a majority of these flights (i.e., many of the aircraft in this sample are smaller, regional jets or private planes). It should be noted that Overture is scheduled to enter service in 2027, at which point many of these older aircraft (e.g., those categorized as Stage 3 below) may no longer be in service.

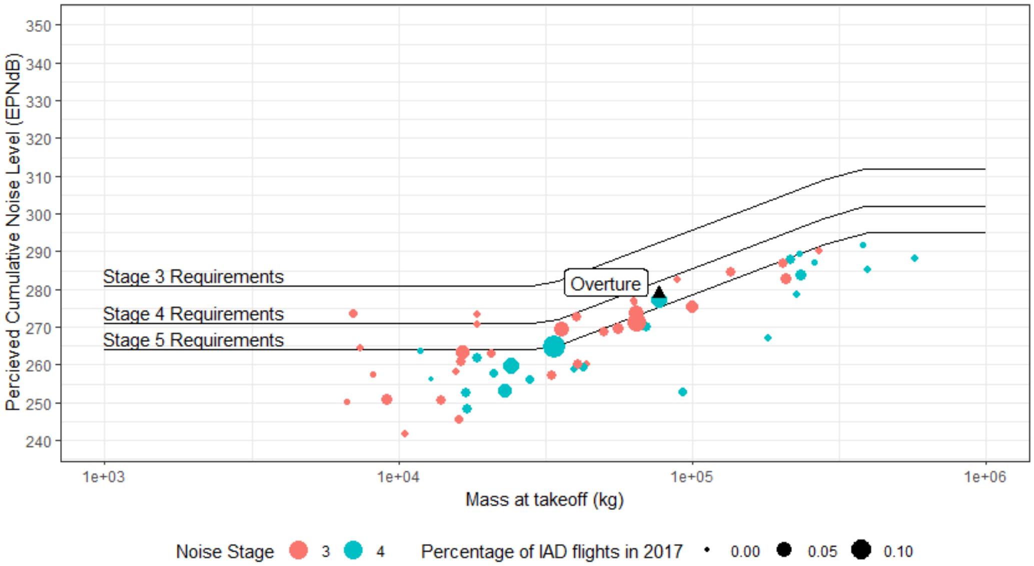


Figure E-1. Overture Noise Estimate Compared with Aircraft Operating out of IAD in 2017

Long-Haul Comparison

Boom expects Overture to initially fly transatlantic or transpacific routes—i.e., routes that are sufficiently long to take advantage of supersonic flight over water. We thus compare the noise of Overture to that of long-haul planes that are likely to offer service on similar routes, specifically flights between North America and Europe (transatlantic) and between North America and Asia (transpacific). These long-haul routes are typically served by wide body jets for which the Centre for Aviation Analysis (CAPA) published data in 2016 (CAPA 2016). These target routes are typically flown by a small group of aircraft; in 2016, this was largely comprised of Airbus (330, 340, 350, and 380) and Boeing (747, 767, 777, and 787) aircraft. Figure E-2 compares the noise levels of these aircraft.

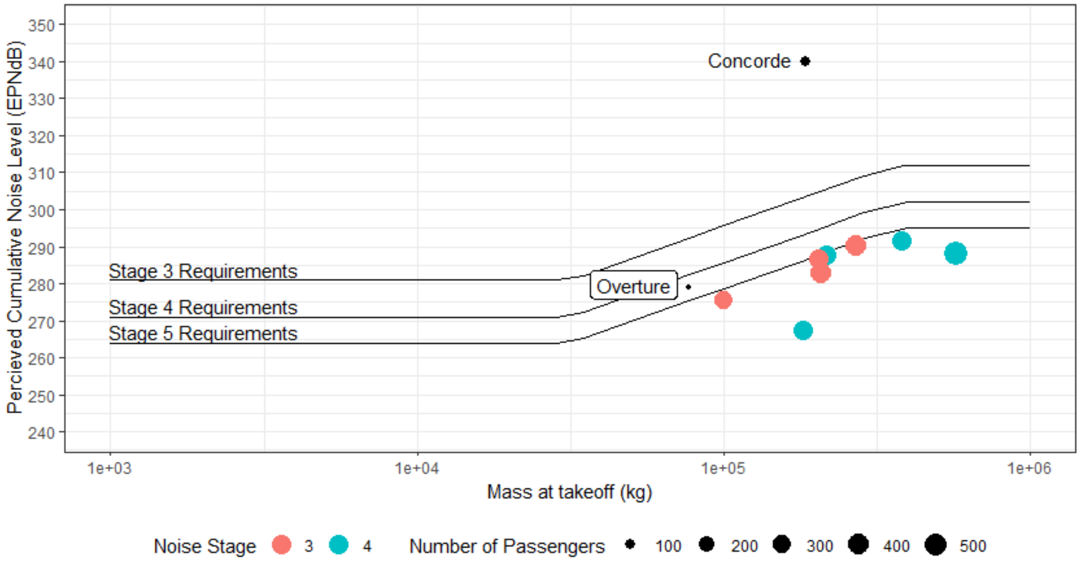
When compared to the current fleet servicing long-haul routes (i.e., wide-bodied planes primarily comprised of larger Airbus and Boeing aircraft), Overture fares much better: the supersonic aircraft would be louder than the aircraft making only 16% of transatlantic and 15% of transpacific flights. Even if Overture met Stage 5 standards, it would not change the noise distribution for transatlantic flights and only slightly for transpacific flights.

Table E-4. Comparison of Overture to Percentage of Long-Haul Flights in 2016

Scenario	**Percent of Flights Quieter than Overture**	
	Transatlantic	Transpacific
Stage 4	16%	15%
Midway Point	16%	15%
Stage 5	16%	6%

Some aircraft that flew transpacific routes in 2016 did not fly across the Atlantic. For example, the B757, which has a noise level in between the midway point and stage 5, flew 9% of transpacific routes but did not fly transatlantic.

Thus, given the service Boom expects Overture to offer, the aircraft will likely not be significantly disruptive as it flies alongside or even replaces aircraft on these long-haul routes. However, it should be noted that Overture's expected capacity (55 passengers) is much lower than that of the other aircraft on these routes: in a typical three-class seating arrangement, the other eight aircraft considered here hold an average of 383 passengers.



The requirements at each stage plotted here are only for 3-engine planes (which includes Overture). The noise levels of the other aircraft can be compared to those of one another, as well as that of Overture, but these should not be considered relative to the plotted standards.

Figure E-2. Overture Noise Estimate Compared with Other Long-Haul Aircraft

Analysis

This analysis shows that Overture would be roughly average for the fleet in use today and quieter than the airplanes on the long-haul routes that it will frequent; even if Overture does not meet the noise levels required by Stage 5, the aircraft will still be quieter than many of the planes traveling the same routes.

However, many aircraft developed prior to 2017 were already able to meet future requirements for LTO noise, and new models will likely continue to exceed the current regulations, creating a larger gap between the noise levels of Overture and new entrants to the fleet. As R&D expands and supersonic technology improves, it is likely that future generations of supersonic airliners will also experience a decrease in LTO noise. The projected noise level of Overture is already markedly less than that of Concorde, demonstrating a huge improvement for LTO noise of supersonic aircraft.

Appendix F.
NASA Supersonics Research and Development

Airframe

NASA has experimented with many methods to maximize aircraft efficiency, focusing on aspects unique to supersonic aircraft (e.g., the slenderness of the vehicle; active systems and passive design techniques to minimize or eliminate the weight penalty associated with flutter or structural dynamics in a supersonic aircraft). NASA research to reduce the weight of subsonic aircraft contributes to this effort. Additional work seeks to limit the draft on supersonic airframes, potentially through laminar flow technologies that reduce friction drag. U.S. and European manufacturers are already using or testing laminar flow technologies at subsonic speeds, which may lead to transferrable lessons for supersonic aircraft. The Boeing 787 incorporates laminar flow on its vertical tail, and Europeans are pursuing flight tests of laminar flow technology (NASA 2004).

Engine

NASA project teams are working to develop new data on engine inlets and fan designs. Current and previous NASA work on fuel efficiency for subsonic aircraft may also be applied to supersonic efforts. A specific area of research interest for NASA is reducing aircraft fuel consumption. Because supersonic aircraft burn more fuel, they are expected to produce greater carbon dioxide emissions than their subsonic counterparts. NASA work therefore intends to improve engine efficiencies and limit fuel consumption. NASA has gathered data to help identify design requirements for supersonic engine combustor components, leveraging existing efforts toward reducing subsonic emissions (i.e., testing subsonic components at conditions representative of the higher altitude, pressure, and temperature conditions of a supersonic engine). These include tests of different fuel injectors and combustor component designs (e.g., to produce fewer pollutants than current offerings [Tacina 2018]).

Through the NASA Research Announcement process, NASA has established a set of collaborative agreements and contracts with industry entities to work on concepts for improved low emission supersonic combustors. Although funding for this area was somewhat decreased after 2015–2017, NASA work on dual-mode combustors continues (e.g., Trefny and Dippold 2017). NASA is funding an emissions effort at MIT to improve global atmospheric modeling of high-altitude emissions (MIT Laboratory for Aviation and the Environment 2014). This information is expected to be shared with industry partners and used to design a unique combustor representative of options for a supersonic engine, which could then be tested.

LTO Noise

U.S. companies are designing their aircraft using expected contributors to estimate LTO noise (i.e., jet, inlet and fan noise), even though aspects of these components are not yet well-understood for supersonic aircraft. NASA is developing new experimental data and analytic capabilities to better predict the noise output of different components, reducing the uncertainty around the expected noise levels of supersonic aircraft. According to interviewees, internal NASA work focuses on jet noise, while contractors are addressing fan noise and other issues.

NASA has Space Act Agreements[1] in place with three U.S. companies pursuing supersonic flight: Aerion, Boom, and Gulfstream. NASA is working with industry entities to assess their potential LTO noise levels, providing the companies actionable information without requiring them to publicly share the details of their configurations. NASA also uses data from internal projects to validate the models (e.g., data from a series of jet noise tests from NASA's work on next-generation technology for LTO noise). The team uses company information to develop models for noise, which can then be used in public discussions regarding the future regulations. This research is crucial, as rulemaking efforts largely rely on aircraft and flight data.

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[1] NASA's Other Transaction Authority, referred to as a Space Act Agreement (SAA), allows it to enter into agreements that are legally distinct from contracts, leases, grants, and cooperative agreements, although certain restrictions apply. SAAs are meant to mirror agreements between two private commercial entities, meaning that elements of the contract, such as reporting requirements and intellectual property rights, can be negotiated. SAAs can be reimbursable (i.e., used by third parties to reimburse NASA for the use of NASA facilities and unique capabilities, such as wind tunnels or engineering expertise; these cover the full or partial cost to NASA of providing the facility or service) or non-reimbursable (i.e., when both NASA and a third party mutually benefit from an agreement. Each participant in a non-reimbursable SAA, including NASA, covers the costs of its part of the agreement, without exchanging funds. These agreements are used for a wide range of activities, including information and data exchanges from private research that NASA has supported) (Crane et al. 2019).

Appendix G.
International Efforts in Supersonic Flight

Although companies in the U.S. are currently the major players pursuing development of supersonic aircraft, these companies intend to fly internationally. This will require workable regulations and standards in the countries where these aircraft will land, take off, and fly over. As such, regulatory approaches and technical efforts abroad are integral to the discussion of U.S. civilian supersonics.

European Commission

Given current priorities (i.e., active efforts to limit emissions and noise around airports) and experience with the Concorde, European sentiments toward supersonic flight are largely negative. Experts (e.g., representatives from the European Commission as well as U.S. aerospace analysts) expect that because these anti-supersonic sentiments have largely been consistent, it is unlikely that European nations would move forward with their own regulations individually; indeed, a European Commission representative expects countries to agree and comply with the positions put forth by the Commission as a whole.

Concerns in Europe focus especially on the environmental impacts of supersonic flight, including carbon dioxide and nitrogen oxide, as well as aircraft and flight noise. Given the desire to avoid an increase in fleet noise, experts in Europe argue that the LTO noise standard for subsonic aircraft should also apply to supersonic aircraft, given that any increase in permitted noise level would contribute negatively to the overall noise at airports and therefore be unacceptable (see Appendix E for a comparison of supersonic airliner noise to that of the current fleet). The Europeans are thus most interested in a stringent regulation; indeed, European Union publications note that one of the main obstacles to supersonic flight is "the loud and sudden sonic boom felt by the populations overflown during the entire cruise" (Rumble 2019b). This perspective is shared by many in Europe's private sector. For example, Airbus' CTO explained that the company's history and competency in supersonic aircraft (e.g., Tornados, Eurofighters) does not necessarily translate to an interest in supersonic aircraft for private use, largely due to market uncertainties and environmental concerns.[1] Instead, Airbus is focusing on technologies to

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[1] At Airbus Innovation Days, CTO Grazia Vittadini shared: "…how is this possibly compatible with the environmental sustainability targets which we are committed to? …we cannot reconcile [in-house] skills and competencies with products where market interest needs to be confirmed and with no reconciliation with the environmental sustainability targets…" (Garcia 2019).

support environmental progress in aviation (e.g., hybrid electric propulsion systems that can reduce noise in aircraft operations) (Garcia 2019).

The European Commission representative expects global demand for at most 40-50 supersonic business jets, a number that they did not expect to increase in the short- or medium-term. The representative did not detail whether Europeans would be willing to buy or fly supersonic aircraft if the U.S. were able to successfully develop the technology; this is especially uncertain given a number of unknowns that will directly impact the viability of such aircraft (i.e., any European interest in supersonics would depend on maintenance, size of aircraft, operation costs, and other issues). The representative also does not expect European companies such as Airbus or Dassault to produce a supersonic plane.

European officials expect to release a call for proposals in 2020 that will focus on accumulating data and information in support of ICAO negotiations regarding supersonic regulations. These could include consideration of a new configuration or aircraft that could fly with less environmental impact. A Commission representative expressed that Europe is particularly open to working with aviation partners on this topic, including Australia, Canada, China, Japan, Russia, and the United States.

RUMBLE

The European Commission is working to determine the public perception of supersonic flight over land through its project RUMBLE (RegUlation and norM for low sonic Boom LEvels), which intends to generate evidence to help determine acceptable noise levels for overland sonic booms. It will also support potential technological efforts to comply with these noise levels. The high-level objective of the program is to support European contributions to a regulatory standard at ICAO (Rumble 2019b), though the outcomes of RUMBLE are expected to influence regulatory authorities at the national (e.g., France's Director General for Civil Aviation) and European (e.g., the European Union's European Aviation Safety Agency) levels as well. Though RUMBLE will outline potential next steps for a future low boom flying demonstrator (i.e., by determining noise level goals), the program is not producing a low boom aircraft design or building an actual demonstrator plane.

RUMBLE is a collaboration between organizations with experience in supersonic aviation in both Europe and Russia,[2] leveraging past supersonic efforts (i.e., Concorde and

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[2] The consortium includes European entities: Airbus SAS, Airbus Group Limited, Airbus Defence and Space GmbH, Dassault Aviation, The European Aeronautics Science Network Technology Innovation Services (EASN-TIS), Zeus GmbH (Germany), Deutsches Zentrum für Luft – und Raumfahrt e.V. (DLR, Germany's civil space agency), Office National d'Études et de Recherches Aérospatiales (ONERA, the French national aerospace research center), École Centrale de Lyon (France), the

the Tu-144, discussed in Appendix A), and the regulatory bodies in both Europe and Russia are involved as well. The project is funded for the period from November 2017 to September 2020; its total budget is €13.2 M ($14.64 M), of which €5 M ($5.55 M) comes from the European Commission's grant agreement for work toward "Reducing Aviation Noise." The team expects to support the potential for European entities to enter the market for civilian supersonic aircraft.

The project will develop and assess tools to predict aircraft sonic booms, validate findings (e.g., through wind tunnel experiments, flight tests), and study human response to sonic booms, contributing to European Union efforts to determine the social acceptability of sonic boom noise (Rumble 2019c). Technical areas of focus include high fidelity predictions through simulation tools to predict the effect of such aspects as lateral booms, temperature inversion; propagation through turbulent atmosphere, and propagation over non-flat ground (e.g., varied topography, urban centers) (Rumble 2019b). The tests will especially consider the effects of the sonic boom on structures and buildings of particular interest to Europe and will also include studies of the impact of low boom on sleep patterns and disturbances. The RUMBLE website notes that the project team hopes to help avoid having the U.S. establish a "regulation-based" monopoly over supersonic jets, given concerns that the U.S. may be the only nation contributing data to a potential regulatory ruling.

Russia

The Zhukovsky Central Aerohydrodynamic Institute (TsAGI) is designing a 60–80 passenger civil supersonic airliner, targeting cruising speeds of approximately Mach 1.6 with a takeoff weight of about 120 tons and a range of about 5,300 miles. The airframe, which some expect will be made of composite materials instead of traditional aluminum, is designed to limit the noise of the sonic boom. Some analysts at TsAGI believe the project will reach a compromise between the energy efficiency of the aircraft and its acoustic effect; studies have indicated that the acoustic impact of this new aircraft can be reduced to a volume of 65 dB (Aerospace 2019). Series production is scheduled for 2030, and each plane is expected to cost $100–120 M (Aerospace 2019). Government representatives (from the Ministries of Aviation as well as Industry and Trade) expect domestic demand for 20–30 aircraft each year and remain optimistic about export opportunities as well.

Norwegian Geotechnical Institute (NGI), Sorbonne Université (France), The University of Oldenburg (Germany), and the private company Anotec Engineering SL (Spain). It also includes Russian entities: the Central Aerohydrodynamic Institute (TsAGI, named after N.E. Zhukovsky), the Flight Research Institute (named after M. M. Gromov), GosNII GA, Moscow Aviation Institute (National Research University), and the Central Institute of Aviation Motors (CIAM) (Rumble 2019a).

The effort builds on previous work in civilian supersonic transport as well as military supersonic developments, such as in the Tu-160M strategic bomber.[3] Russian efforts to develop a civilian supersonic aircraft in the early 2000s were led by Sukhoi. Sukhoi attempted to develop two supersonic aircraft: a 5–8 person business jet named the S-21 and a 30–50 person passenger jet named the S-51. The efforts included engine and aerodynamic testing and relied on partnerships with Gulfstream and later Dassault (Global Security 2019). Current Russian supersonic plans are likely to build on this work.

The Russian company Tupolev is working on a 30-passenger business jet based on the TsAGI passenger aircraft design (Aerospace 2019). The aircraft is intended to reach speeds of Mach 1.3 to 1.6, with 30 seats in the cabin. The first flight is scheduled for 2027, and the cost of the development program is estimated at approximately $2 B. However, some Russian researchers are skeptical of supersonics in general; their major concerns include fuel consumption and maintenance costs (Aerospace 2019).

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[3] In early 2018, Vladimir Putin mentioned the possibility of using the Tupolev Tu-160M2 bomber to develop a supersonic business jet (Karnozov 2018). In early 2019, Putin emphasized his interest in supersonic civilian flight: “We now need to go back to supersonic business travel” (Intelligent Aerospace, 2019).

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Abbreviations

AETD	Adaptive Engine Technology Development
ARMD	Aeronautics Research Mission Directorate
ATC	air traffic control
CAEP	Committee on Aviation Environmental Protection
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
EIS	environmental impact statement
EPA	Environmental Protection Agency
EPNdB	Effective Perceived Noise in decibels
FAA	Federal Aviation Administration
FY	fiscal year
GE	General Electric
ICAO	International Civil Aviation Organization
IDA	Institute for Defense Analyses
ILS	instrument landing system
LTO	landing and takeoff
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Agency
nm	nautical miles
NoisedB	Noise Database
OSTP	Office of Science and Technology Policy
PLdB	perceived level (of noise) in decibels
QSF18	Quiet Supersonic Flight 2018
QSTA	Quiet Supersonic Technology Airliner
QueSST	Quiet Supersonic Transport
R&D	research and development
RUMBLE	Regulation and norm for low sonic boom levels
SST	Supersonic Transport
STPI	Science and Technology Policy Institute
TRL	technology readiness level

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14. ABSTRACT

Today’s supersonic aircraft companies anticipate that the market can support several types of vehicles, including both airliners and business jets. The U.S. Government can facilitate leadership in civilian supersonics by removing relevant regulations and unnecessary obstacles, ensuring that applicable regulations are “economically reasonable, technologically practicable, and appropriate for the applicable aircraft” (49 U.S.C. § 44715). The White House Office of Science and Technology Policy (OSTP) asked the IDA Science and Technology Policy Institute (STPI) to assess the potential future of supersonic civilian aircraft, offering options that the Federal Government may consider, as appropriate, to support the commercial supersonic flight industry. These recommendations will complement, inform, and possibly accelerate activities undertaken by the Federal Aviation Administration (FAA) under the FAA Reauthorization Act of 2018 (Pub. L. 115–254 Section 181) as well as ongoing efforts within NASA.

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